weather permitting

British Council Ireland and
the Hamilton Mathematics Institute present

Four Lectures on the Weather

Weather Forecasting: From Art to Science

Peter Lynch
Meteorology & Climate Centre
School of Mathematical Sciences
University College Dublin

Outline of this Lecture

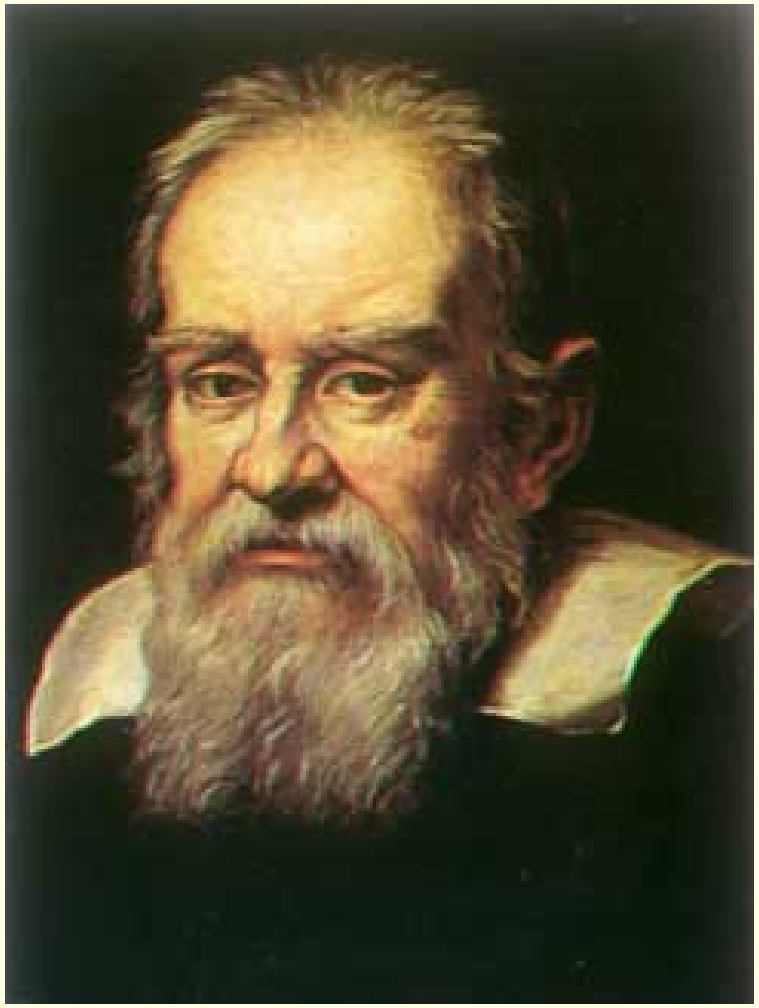
- **The Emergence of the Science of Meteorology**
- **The Development of Numerical Weather Prediction**
- **Modern Computer Weather Forecasting**
- **An Example: The Great Flood of 1953**

The central theme of the lecture will be the remarkable progress which has been made over the past fifty years in our ability to predict the behaviour of the atmosphere over a wide range of time-scales.

This is thanks to the power of mathematics.

Money makes the world go round

Galileo Galilei (1564–1642)



Galileo formulated the basic law of falling bodies, which he verified by careful measurements.

He constructed a telescope, with which he studied lunar craters, and discovered four moons revolving around Jupiter.

Galileo is credited with the invention of the Thermometer.

Galileo's Thermometer

The Galileo Thermometer is a popular modern *collectable* and an attractive decoration.

As temperature rises, the fluid expands and its density decreases.

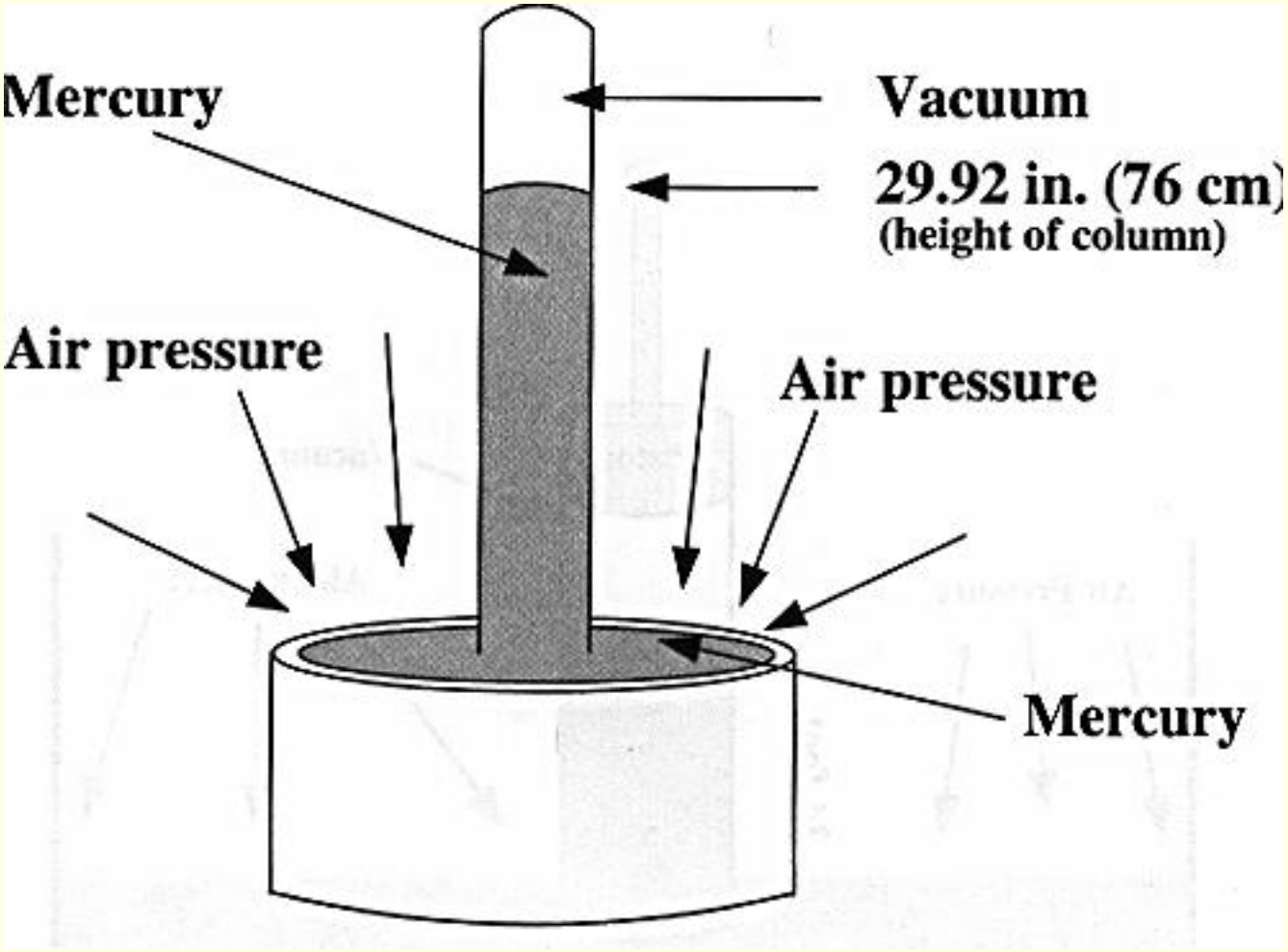
The reduced buoyancy causes the glass baubles to sink, indicating temperature changes.

Galileo's Ace Post-Doc.

Evangelista Torricelli (1608–1647), a student of Galileo, devised the first accurate barometer.

Torricelli inventing the barometer

Barometric Pressure



The relationship between the height of the mercury column and the character of the weather was soon noticed.

Isaac Newton (1642-1727)

Newton established the fundamental principles of Dynamics.

He formulated the basic law of Gravitation.

He produced monumental results in Celestial Mechanics.

He laid the foundation for differential and integral Calculus.

He made fundamental contributions to Optics.

Arguably the greatest scientist the world has ever known.

Newton: the Inventor of Science

John Banville, in his work *The Newton Letters*, goes so far as to write that 'Newton invented science'.

This is a provocative and thought-provoking claim.

Newton's Law of Motion

The rate of change of momentum of a body is equal to the sum of the forces acting on the body.

If $\mathbf{F}$ is the total applied force, Newton's Second Law gives

$$\frac{d\mathbf{p}}{dt} = \mathbf{F}\,.$$

The acceleration $\mathbf{a}$ is the rate of change of velocity, that is, $\mathbf{a} = d\mathbf{V}/dt$. If the mass m is constant, we have

$$\mathbf{F} = m\mathbf{a}\,.$$

Force = Mass $\times$ Acceleration.

Euler's Equations for Fluid Flow

Leonhard Euler

- **Born in Basel in 1707.**
- **Died 1783 in St Petersburg.**
- **Formulated the equations for incompressible, inviscid fluid flow:**

$$\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} + \frac{1}{\rho} \nabla p = \mathbf{g} \,.$$

$$\nabla \cdot \mathbf{V} = 0$$

The Navier-Stokes Equations

$$\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} + \frac{1}{\rho} \nabla p = \nu \nabla^2 \mathbf{V} + \mathbf{g}^\star \,.$$

The Navier-Stokes Equations describe how the change of velocity, the acceleration of the fluid, is determined by the pressure gradient force, the gravitational force and the frictional force.

For motion relative to the rotating earth, we must include the Coriolis force:

$$\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} + 2\boldsymbol{\Omega} \times \mathbf{V} + \frac{1}{\rho} \nabla p = \nu \nabla^2 \mathbf{V} + \mathbf{g} \,.$$

The Inventors of Thermodynamics

The Equations of the Atmosphere

GAS LAW (Boyle's Law and Charles' Law.)
Relates the pressure, temperature and density
CONTINUITY EQUATION
Conservation of mass; air neither created nor distroyed
WATER CONTINUITY EQUATION
Conservation of water (liquid, solid and gas)
EQUATIONS OF MOTION: Navier-Stokes Equations
Describe how the change of velocity is determined by the pressure gradient, Coriolis force and friction
THERMODYNAMIC EQUATION
Determines changes of temperature due to heating or cooling, compression or rarifaction, etc.

Seven equations; seven variables (u, v, w, ρ, p, T, q)**.**

The Primitive Equations

$$\frac{du}{dt} - \left(f + \frac{u\tan\phi}{a}\right)v + \frac{1}{\rho}\frac{\partial p}{\partial x} + F_x = 0$$

$$\frac{dv}{dt} + \left(f + \frac{u\tan\phi}{a}\right)u + \frac{1}{\rho}\frac{\partial p}{\partial y} + F_y = 0$$

$$p = R\rho T$$

$$\frac{\partial p}{\partial y} + g\rho = 0$$

$$\frac{dT}{dt} + (\gamma - 1)T\nabla\cdot\mathbf{V} = \frac{Q}{c_p}$$

$$\frac{\partial \rho}{\partial t} + \nabla\cdot\rho\mathbf{V} = 0$$

$$\frac{\partial \rho_w}{\partial t} + \nabla\cdot\rho_w\mathbf{V} = [\text{Sources} - \text{Sinks}]$$

Seven equations; seven variables $(u, v, w, p, T, \rho, \rho_w)$**.**

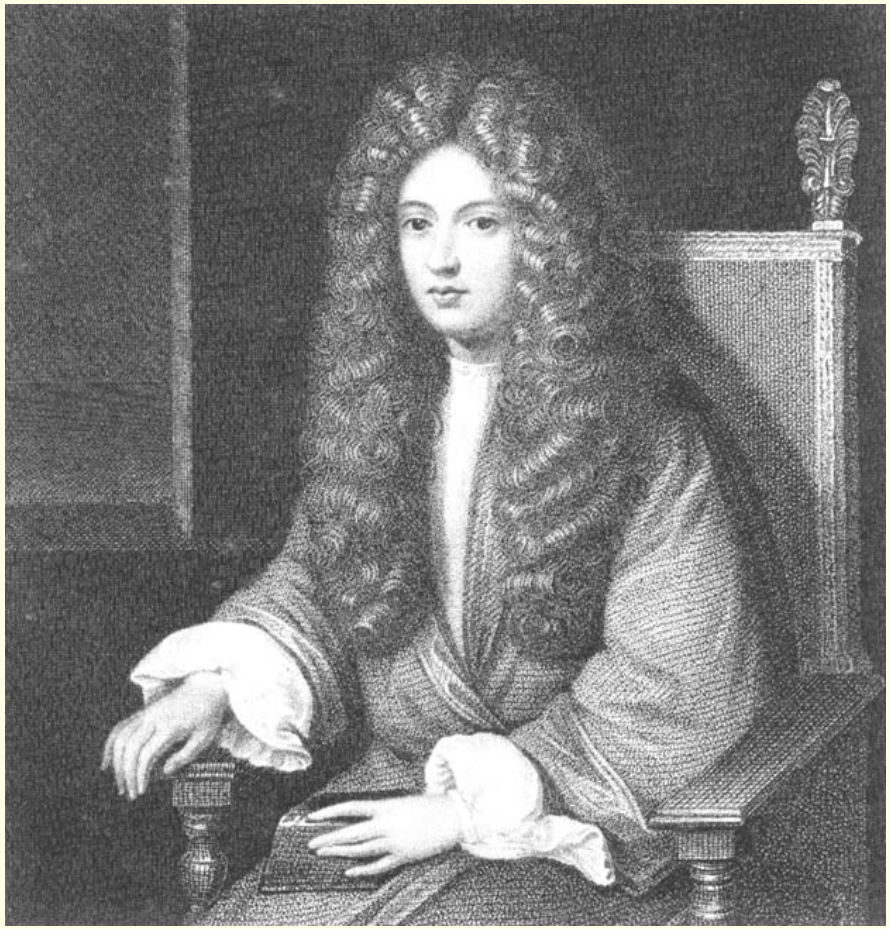
Scientific Weather Forecasting in a Nut-Shell

- The atmosphere is a physical system
- Its behaviour is governed by the laws of physics
- These laws are expressed quantitatively in the form of mathematical equations
- Using observations, we can specify the atmospheric state at a given initial time: "Today's Weather"
- Using the equations, we can calculate how this state will change over time: "Tomorrow's Weather"

- The equations are very complicated (non-linear) and a powerful computer is required to do the calculations
- The accuracy decreases as the range increases; there is an inherent limit of predictibility.

Irish Scientists who have made Contributions to Meteorology

Robert Boyle (1627-1691)



Robert Boyle was born in Lismore, Co. Waterford.

He was a founding fellow of the Royal Society.

Boyles Law:

Boyle formulated the relationship between pressure and volume of a fixed mass of gas at fixed temperature.

$$p \propto 1/V$$

Richard Kirwan (1733–1812)

Richard Kirwan was born in Co. Galway.

He was a noted Chemist, Mineralogist, Meteorologist and Geologist

He was an early President of the Royal Irish Academy

He anticipated the concept of **air-masses**

He believed that the Aurora Borealis resulted from combustion of equatorial air.

Francis Beaufort (1774–1857)

Born near Navan in Co. Meath.

Served in the Royal Navy in the Napoleonic wars.

Helped to establish a telegraph line from Dublin to Galway.

Appointed Hydrographer to the Royal Navy in 1829, a post he held until the age of 81.

Promoted Rear Admiral in 1846.

Knight Commander of the Bath two years later.

Best remembered for the **Beaufort scale**, for estimating winds at sea.

John Tyndall (1820–1893)

Born in 1820 at Leighlinbridge, Carlow.

Studied with Robert Bunsen in Marburg, 1848.

Associated with the Royal Institution from 1853. Assistant to Michael Faraday.

Published more than 16 books and 145 papers.

Tyndall and the Greenhouse Effect

- Tyndall wrote that, without water vapour, the Earth's surface would be *held fast in the iron grip of frost*.
- He showed that water vapour, carbon dioxide and ozone are strong absorbers of heat radiation.
- This is what we now call the **Greenhouse Effect**.
- Tyndall speculated how changes in water vapour and carbon dioxide could be related to climate change.

George G Stokes, 1819–1903

- **Founder of modern hydrodynamics**
- **Stokes' Theorem**
- **Stokes Drag and Stokes' Law**
- **Fluorescence**
- **Stokes Drift**
- **Stokes Waves**
- **Campbell-Stokes Sunshine Recorder**
- **Navier-Stokes Equations**

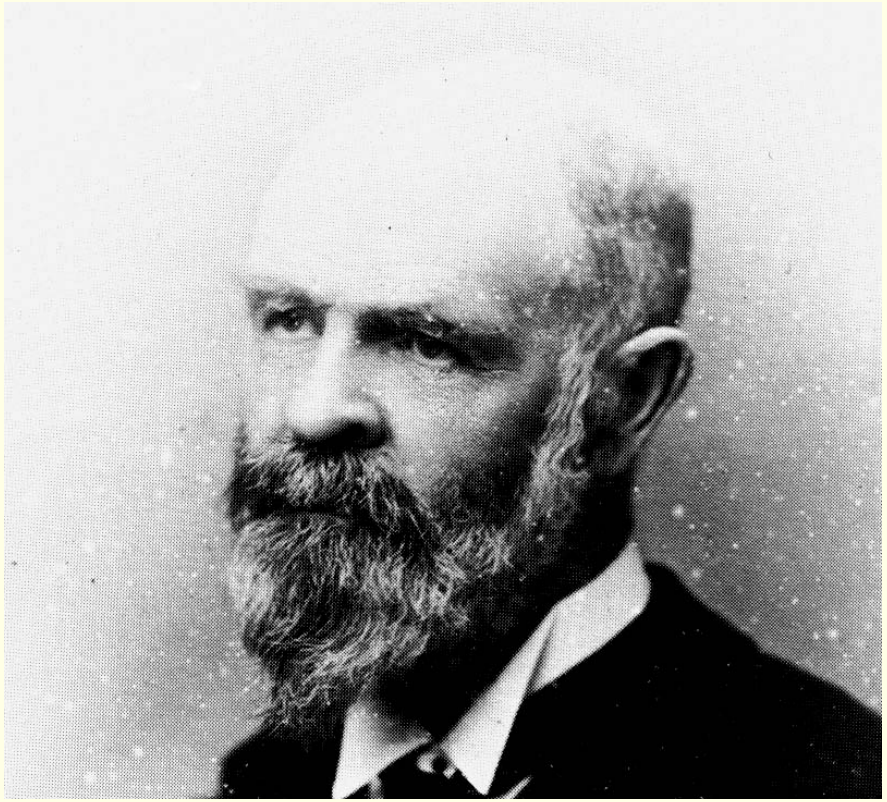
William Thompson (1824–1907)

Sir William Thompson, 1st Baron Kelvin of Largs, born in Belfast. His family moved to Glasgow in 1832.

Kelvin was one of the most brilliant scientists of the 19th century.

- Professor of Natural Philosophy in Glasgow at age 22
- Pioneering research into electrodynamic and thermoelectric properties of matter.
- Developed the foundations of thermodynamics.
- Introduced the absolute scale of temperature; zero at -273°.
- Knighted 1866, after completion of the Atlantic Telegraph cable.
- Invented a tide machine, which predicted the water levels for a year in advance.

Robert Henry Scott (1833–1916)



Robert Scott, born in Dublin, 1833.

Founder of Valentia Observatory

First Director of the British Meteorological Office.

Osborne Reynolds, 1842–1912

- Born in Belfast, 1842
- Graduated from Queens College, Cambridge in 1867
- First Professor of Engineering at Owens College, Manchester, in 1868
- Work in heat transfer led to major developments in boiler and condenser design
- The Reynolds Number, a criterion for turbulence.

$$\mathrm{Re} \equiv \frac{VL}{\nu}$$

Met Éireann-UCD Link

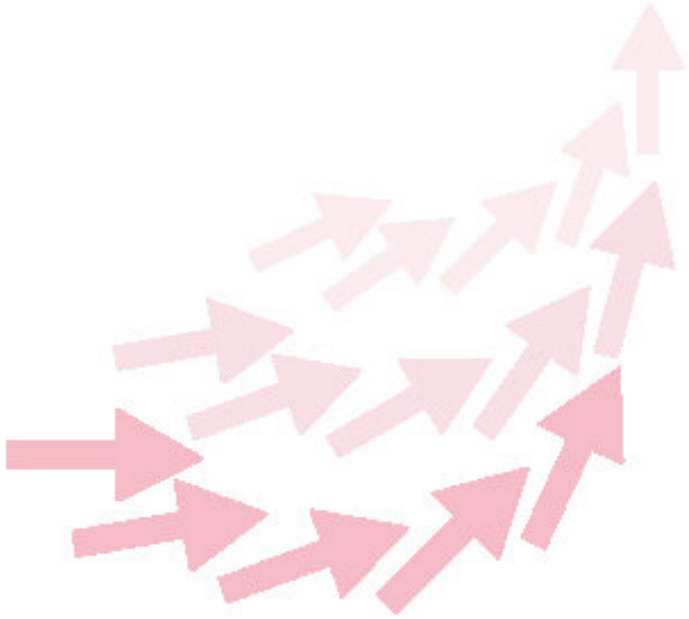
With the exception of Kirwan, all these scientists, though born in Ireland, made their names abroad.

All that has now changed!!!

In October 2003, Met Éireann and UCD signed an agreement to establish a Meteorology & Climatology Centre.

- **The Centre is based in the School of Mathematical Sciences in UCD Belfield**
- **A post-graduate course commenced in September, 2004**
- **Undergraduate meteorology modules are being designed.**

Our Stokeses and Kelvins no longer have to leave Ireland to make their marks on meteorology.



UCD DUBLIN

'...because weather affects
everything we do'

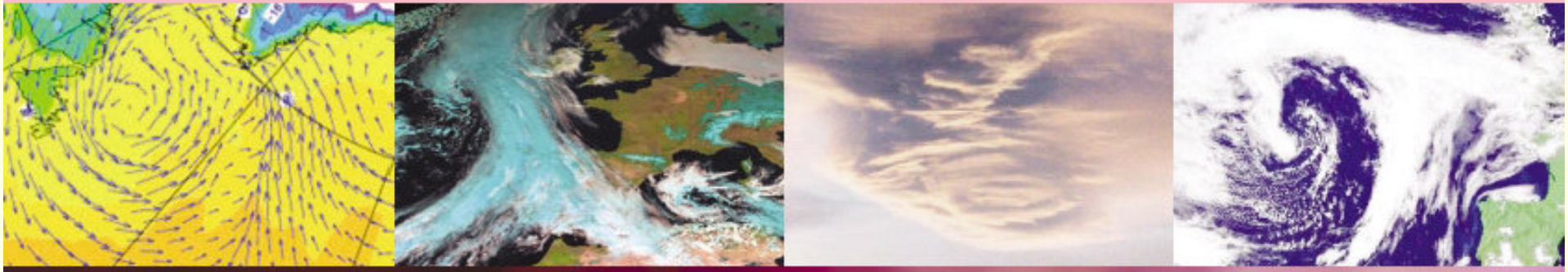
M.Sc. Meteorology

A new M.Sc. in Meteorology in partnership with Met Éireann covering Theory and Applications.

www.ucd.ie/meteorology

M.Sc. Meteorology

A new M.Sc. in Meteorology in partnership with Met Éireann covering Theory and Applications.



Modules:

- General and Physical Meteorology
- Climate and Synoptic Meteorology
- Dynamic Meteorology
- Numerical Weather Prediction

Hands on experience in an extended applied project, field trip and practical applications. For graduates in science and engineering with a strong mathematical background

www.ucd.ie/meteorology

Vilhelm Bjerknes (1862–1951)

Bjerknes' 1904 Manifesto

Objective:
To establish a science of meteorology

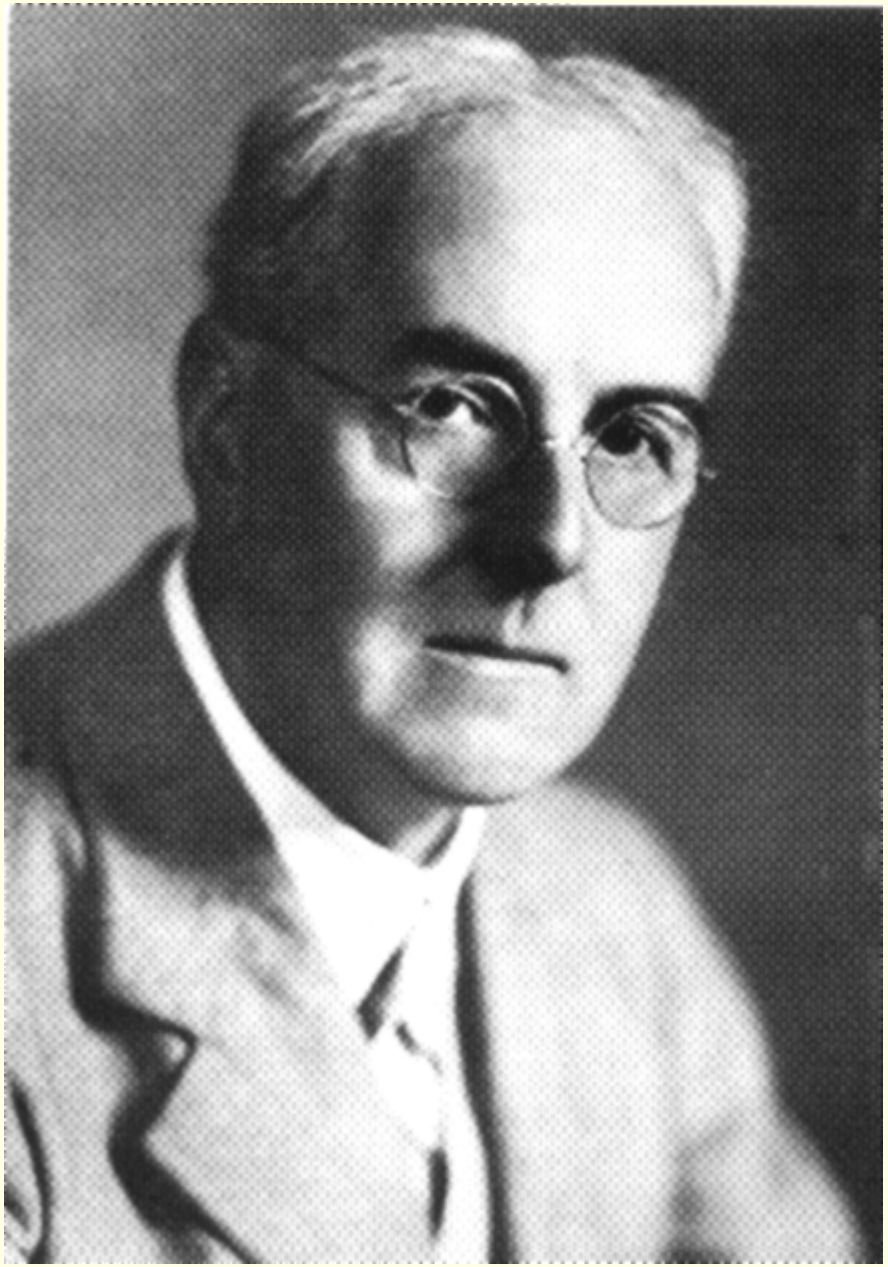
Purpose:
To predict future states of the atmosphere.

Necessary and sufficient conditions for the solution of the forecasting problem:

1. **A sufficiently accurate knowledge of the state of the atmosphere at the initial time**
2. **A sufficiently accurate knowledge of the laws according to which one state of the atmosphere develops from another."**

Step (1) is Diagnostic. **Step (2) is Prognostic.**

Lewis Fry Richardson, 1881–1953.



During WWI, Richardson computed by hand the pressure change at a single point.

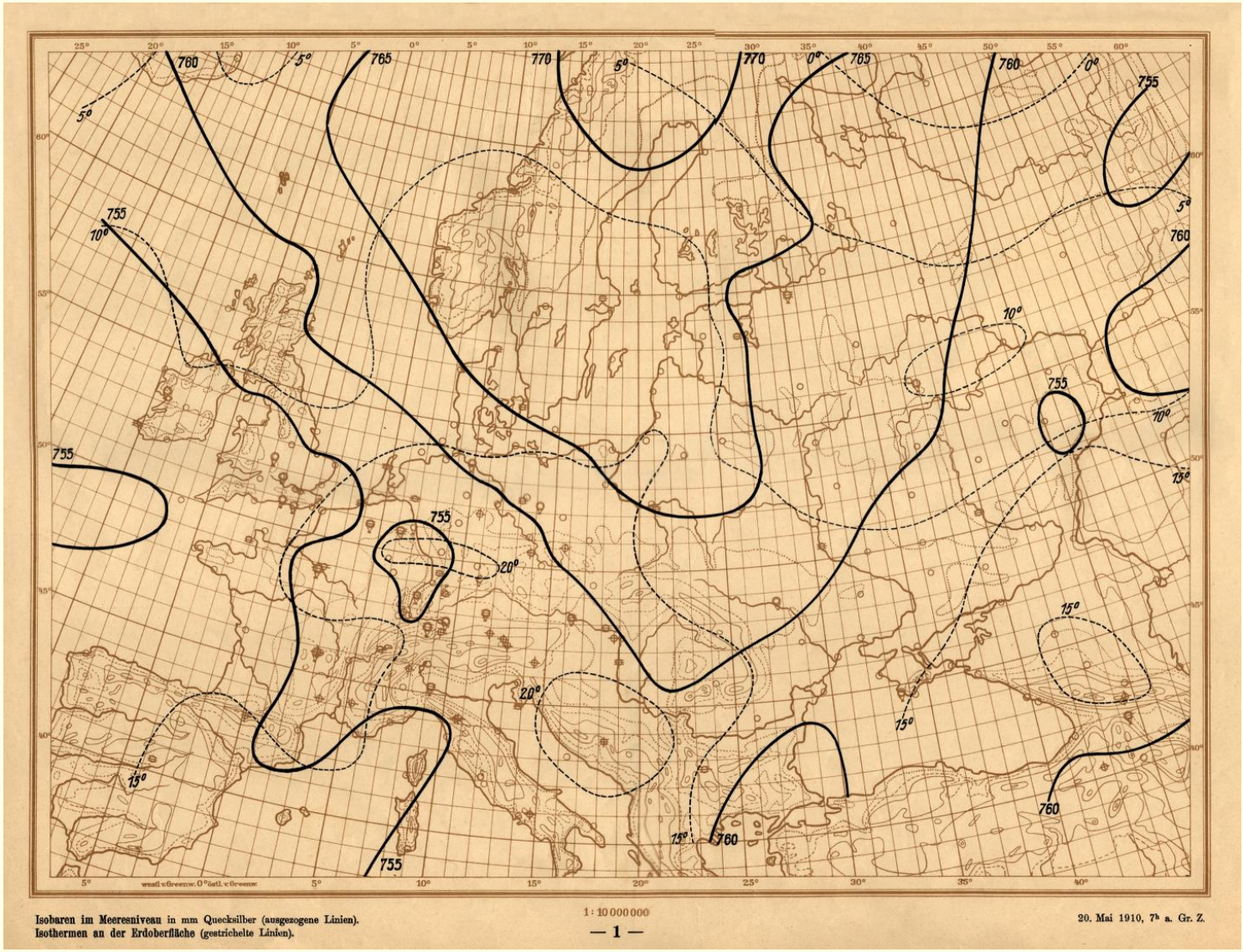
It took him two years !

His 'forecast' was a catastrophic failure:

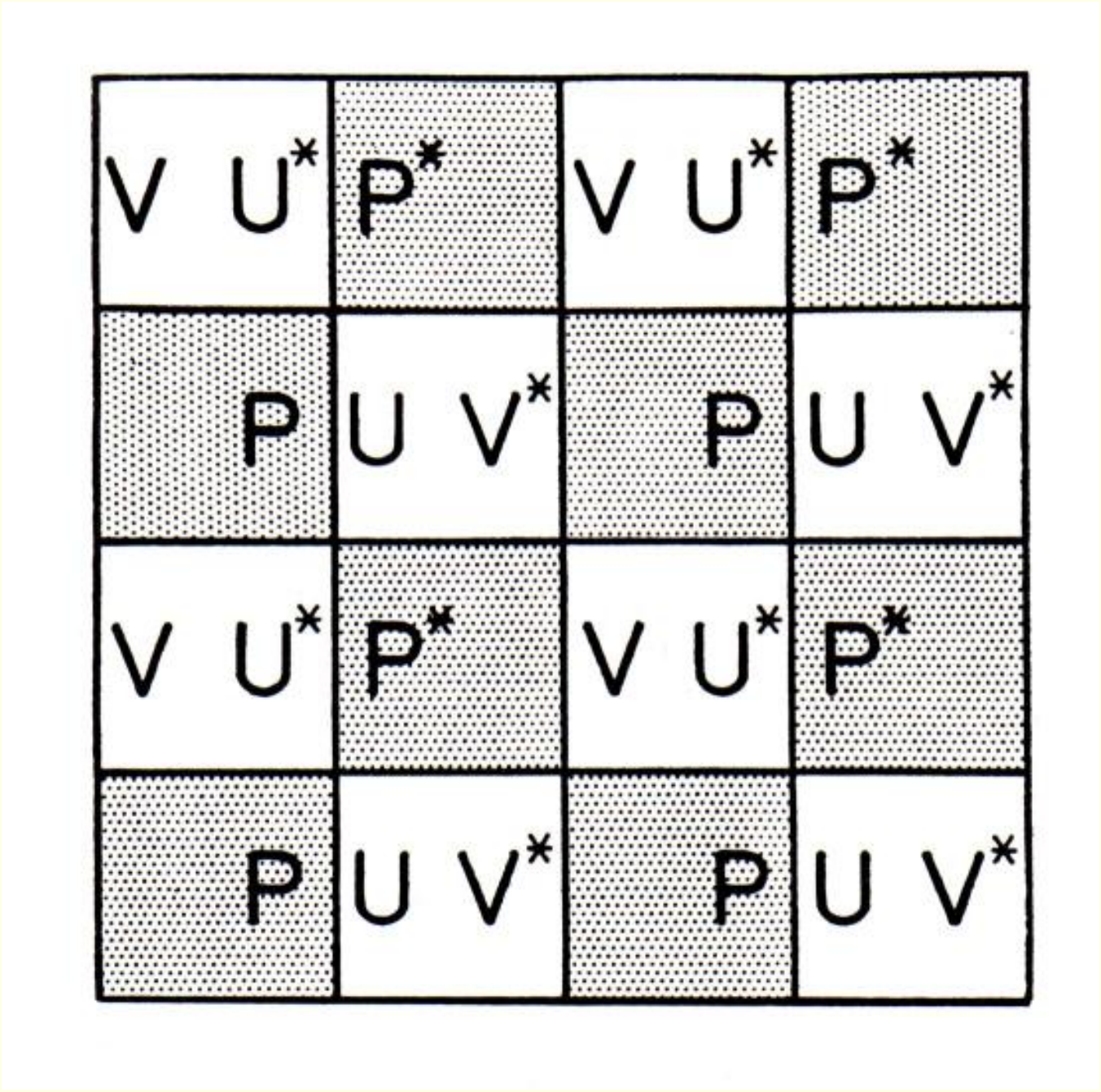
$$\Delta p = 145 \text{ hPa in 6 hours}$$

But his method was unimpeachable.

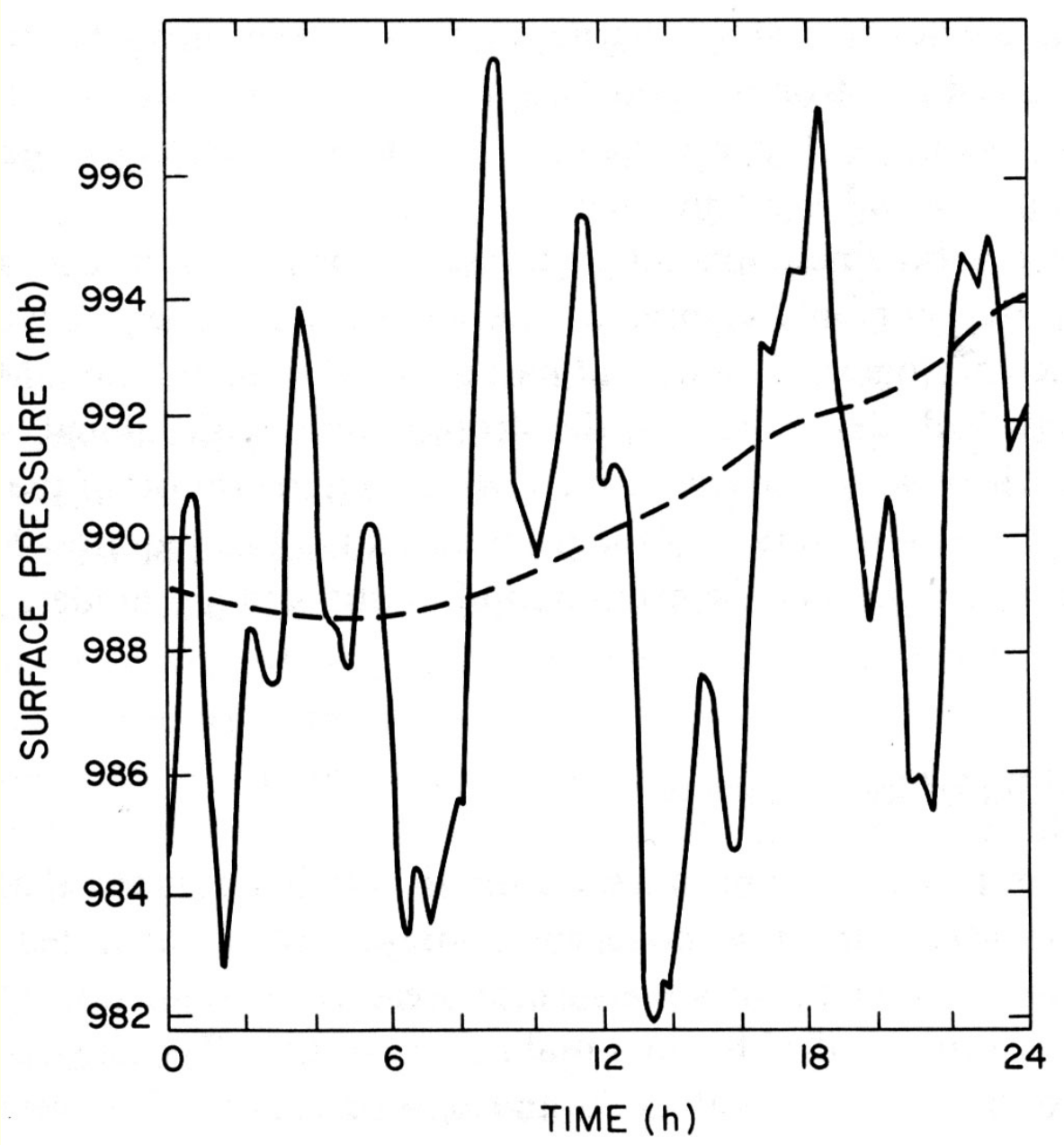
The Leipzig Charts for 0700 UTC, May 20, 1910



Bjerknes' sea level pressure analysis.



Richardson Grid (also called an Arakawa E-grid)



Evolution of surface pressure before and after NNMI.

(Williamson and Temperton, 1981)

Richardson's Forecast Factory

©François Schuiten

64,000 Computers: The first Massively Parallel Processor

Advances since Bjerknes and Richardson

- ***Dynamic Meteorology***

  Quasi-geostrophic Theory. Baroclinic Instability

- ***Numerical Analysis***

  CFL Stability Criterion. Semi-Lagrangian Techniques

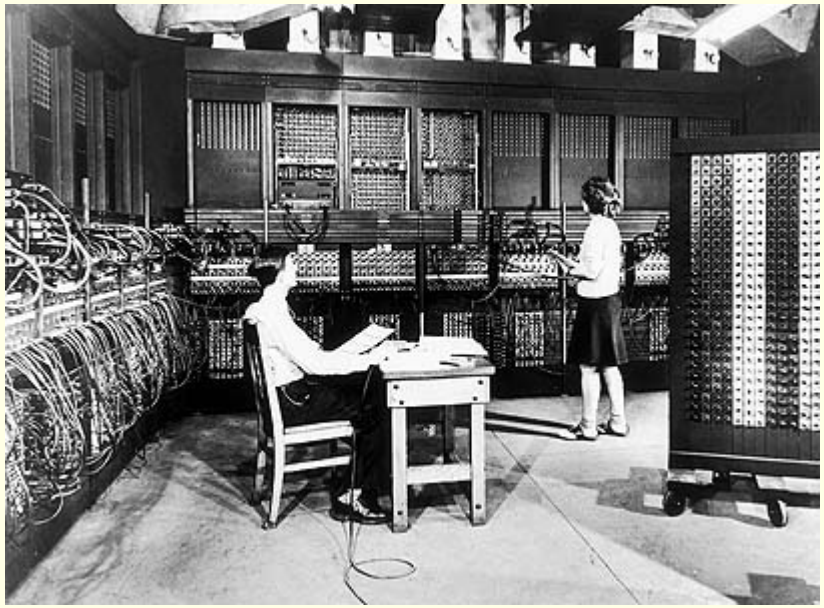
- ***Atmopsheric Observations***

  Radiosondes. Satellite Instrumentation

- ***Electronic Computing***

  ENIAC . . . Moore's Law . . . IBM Blue Gene

The ENIAC

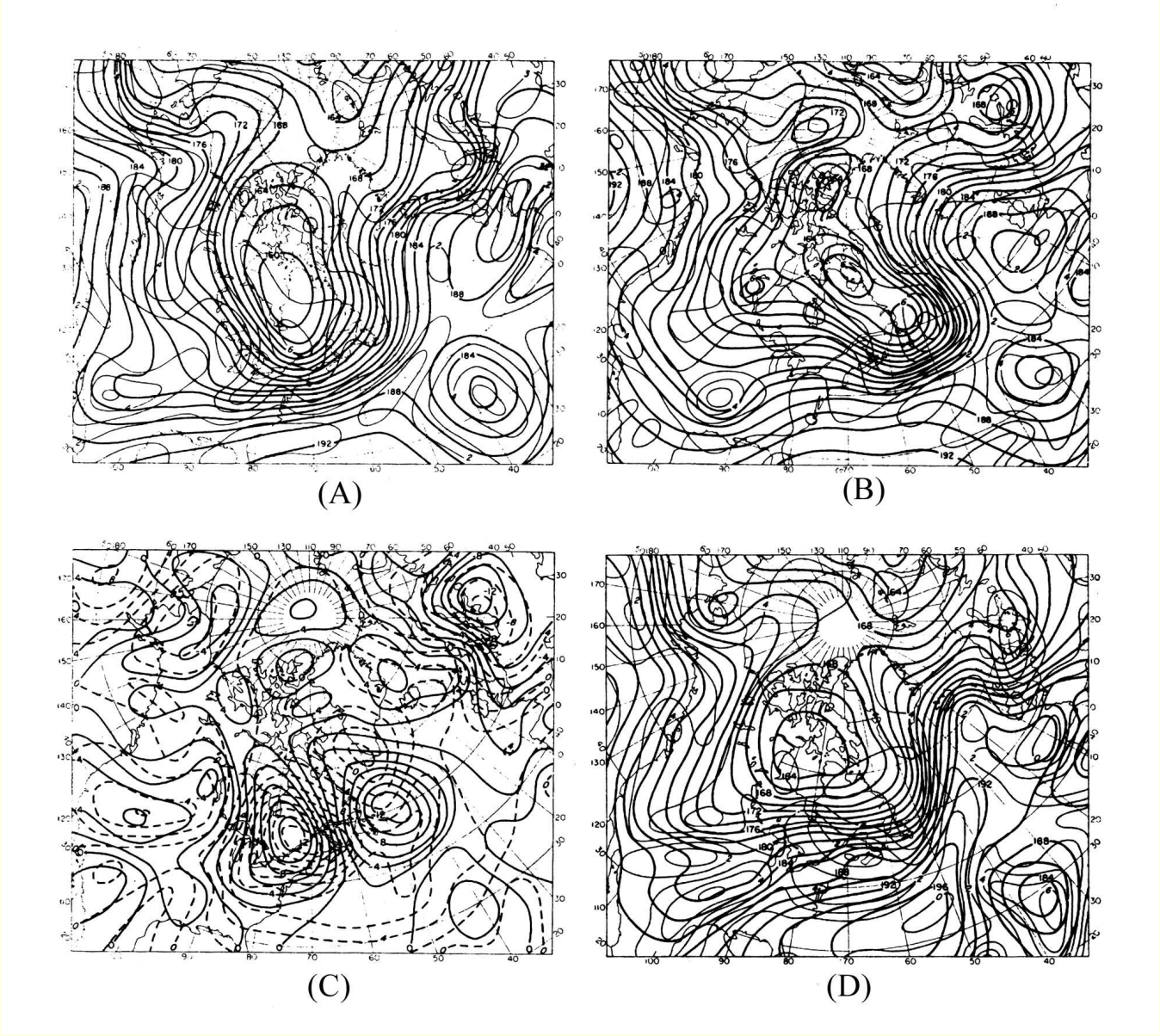


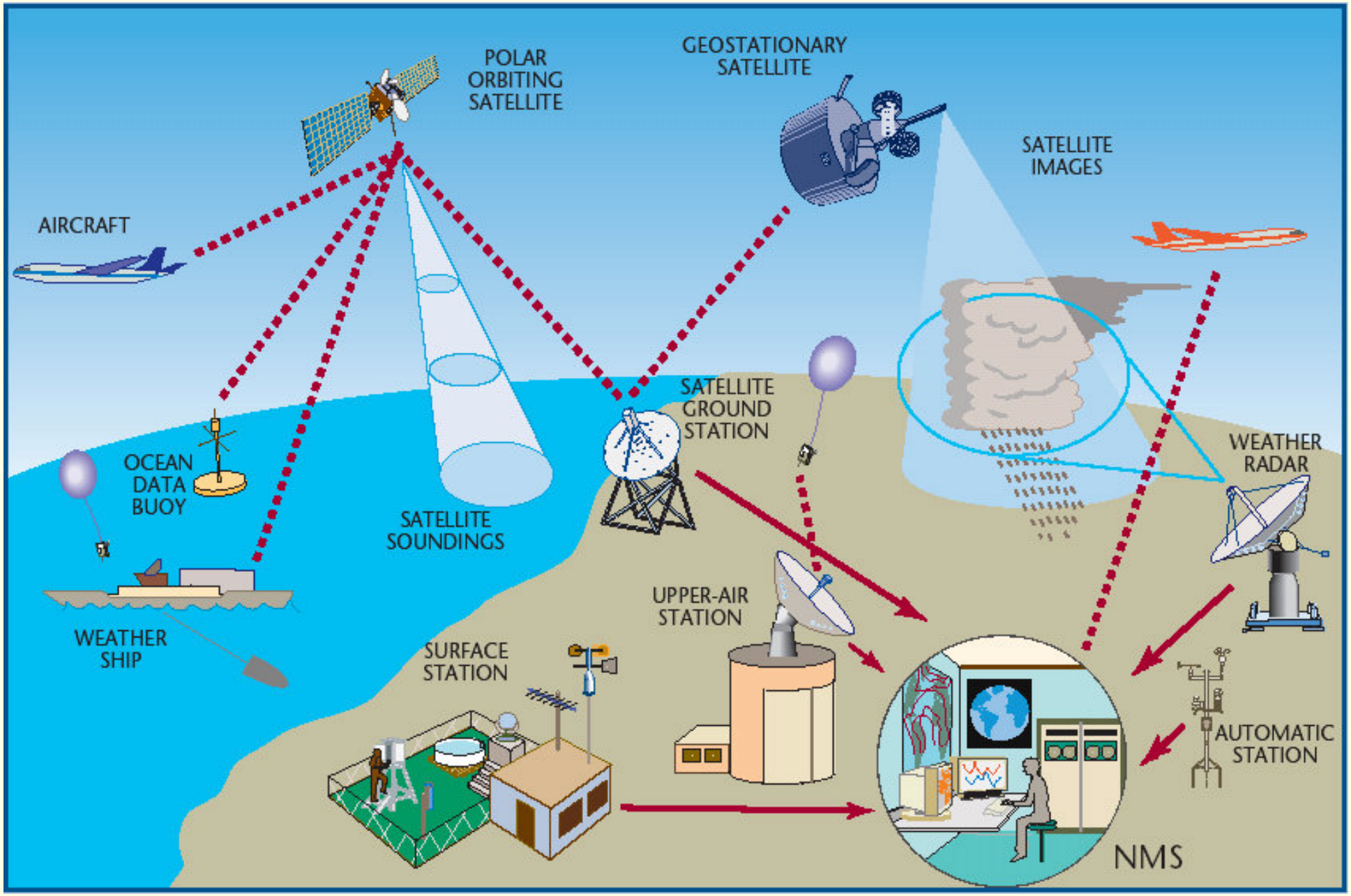
The ENIAC (Electronic Numerical Integrator and Computer) was the first multipurpose programmable electronic digital computer.
It had:

- **18,000 vacuum tubes**
- **70,000 resistors**
- **10,000 capacitors**
- **6,000 switches**

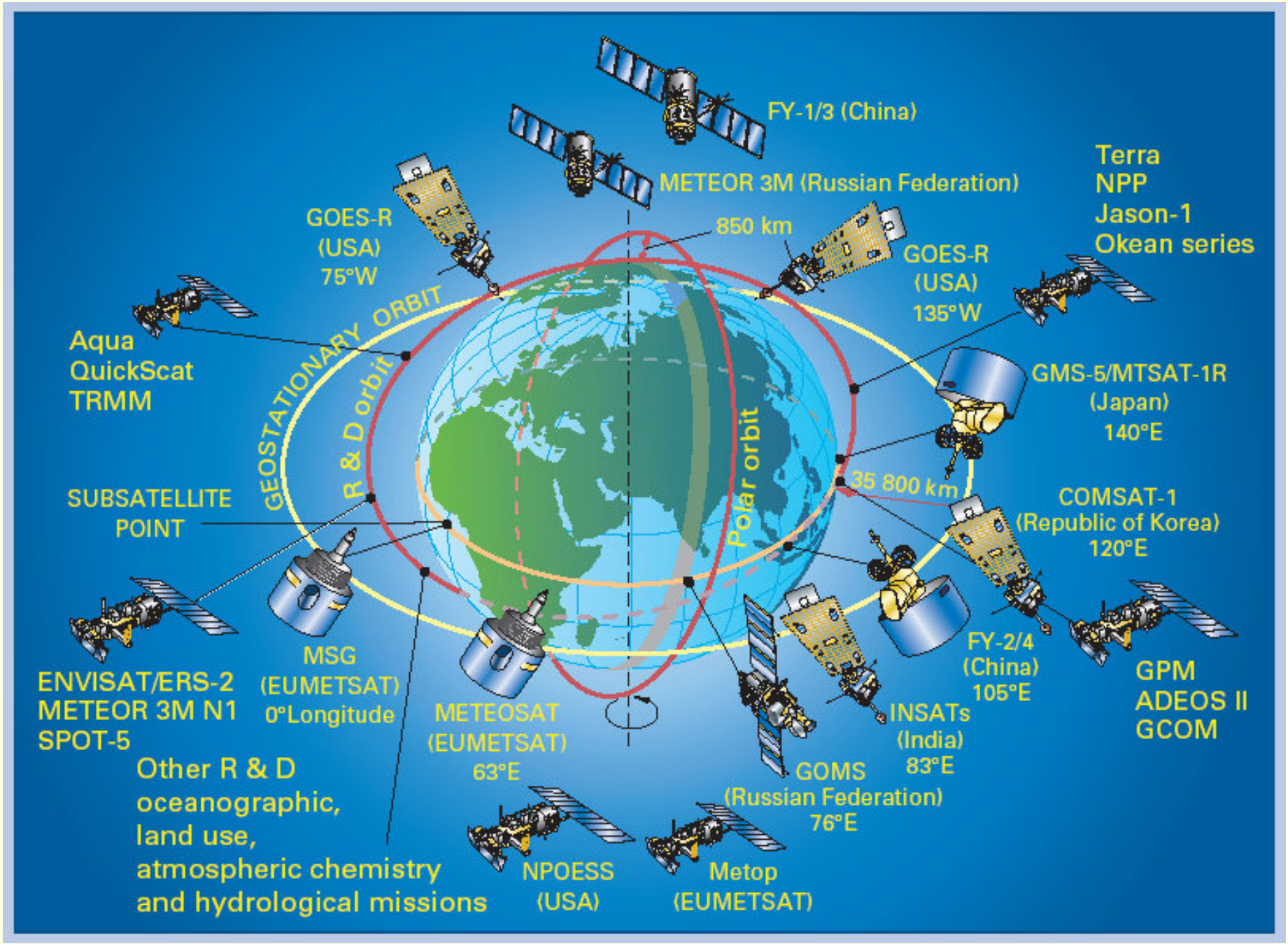
Power Consumption: 140 kWatts

1950: The First Computer Forecast

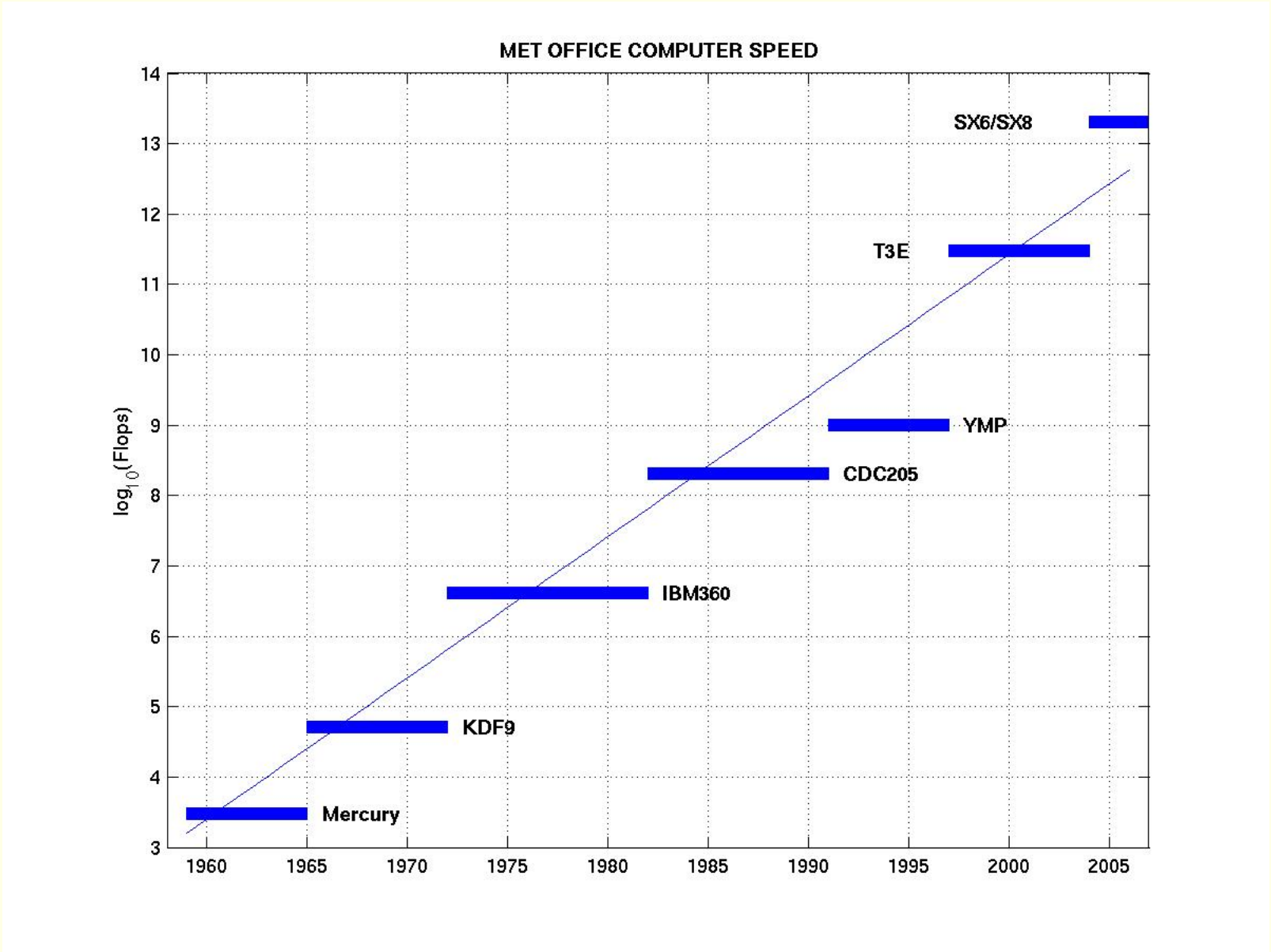




The global observing system today.



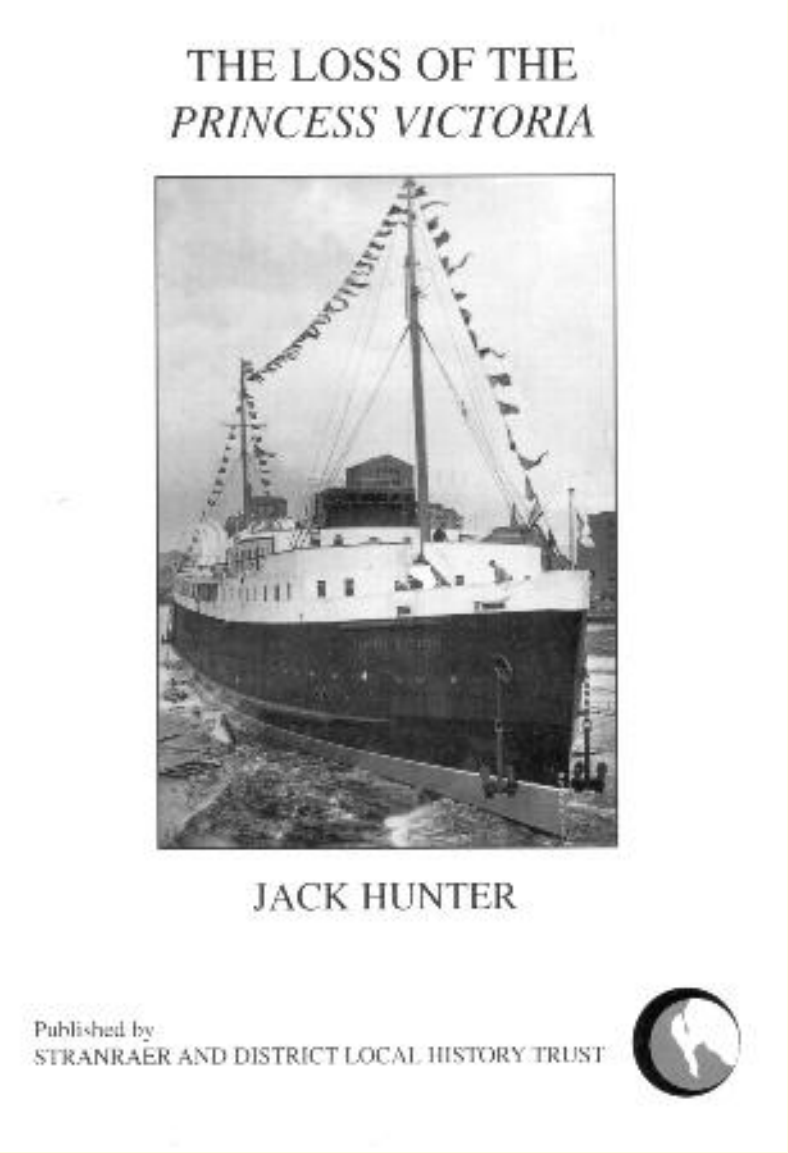
Meteorological satellite network today.



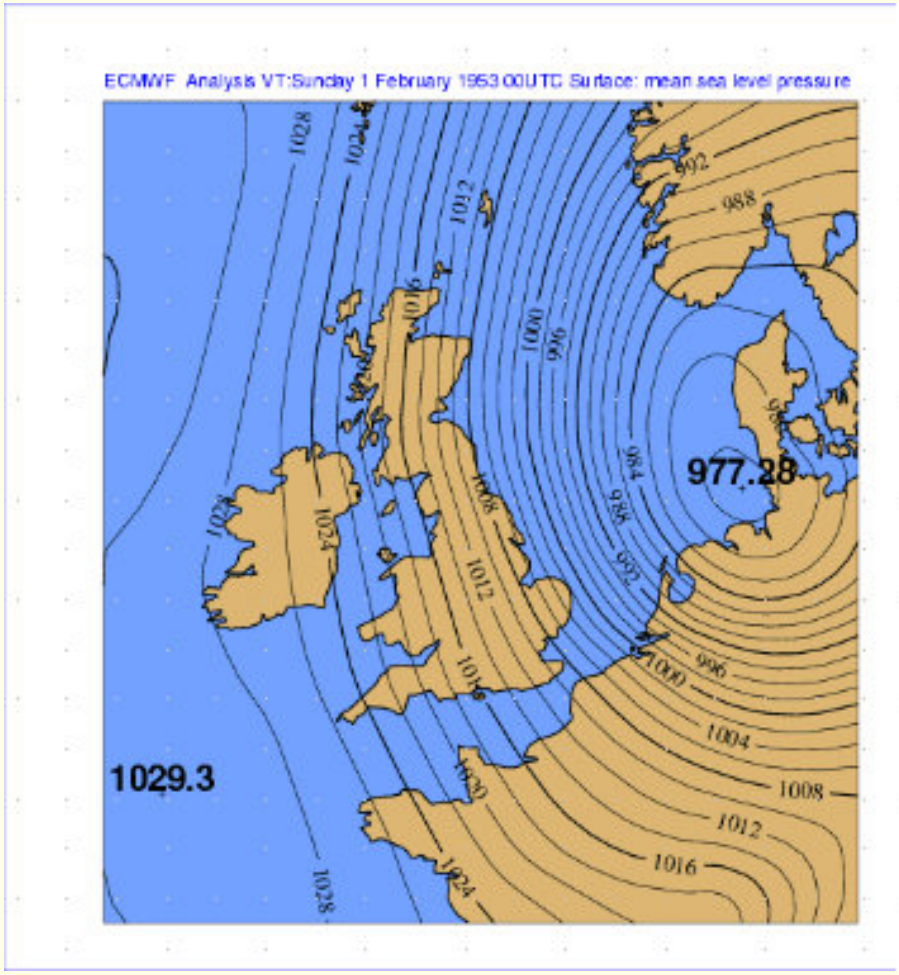
Processing speed of Met Office computers 1959–2005

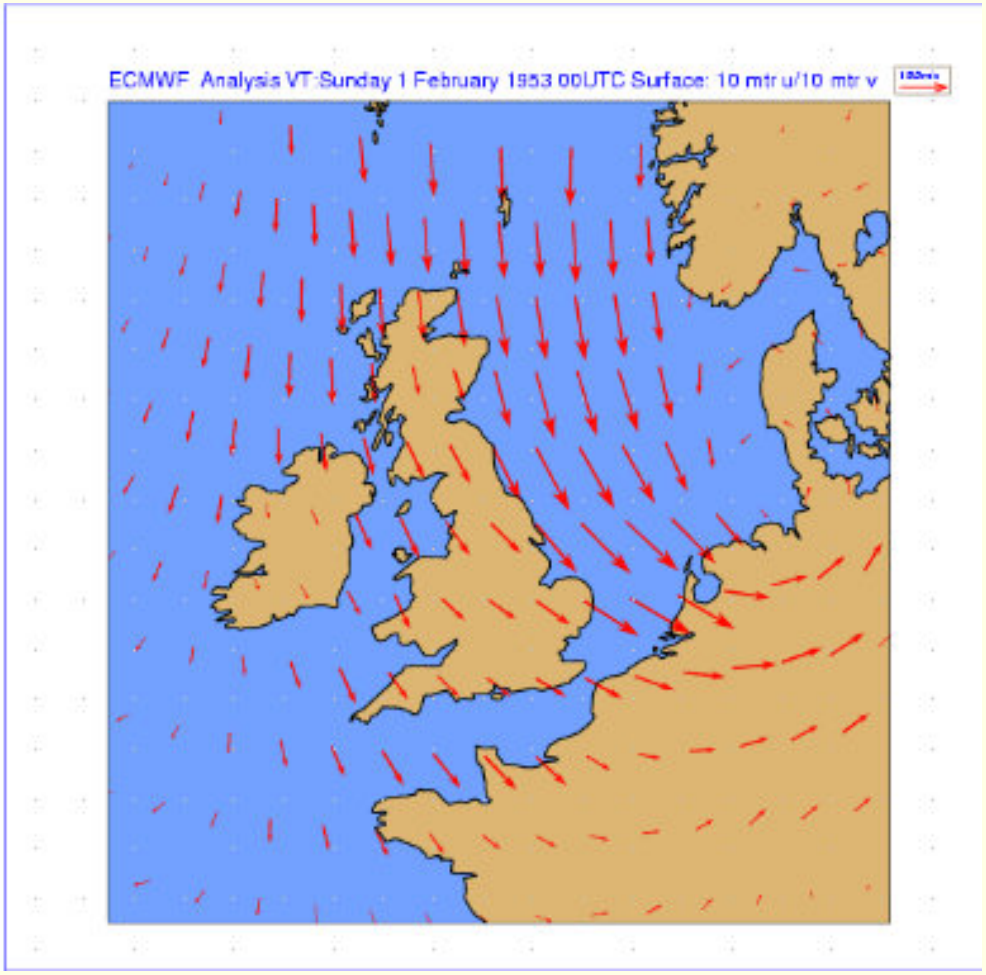
(data from http://www.metoffice.gov.uk)

The Great Flood of 1953



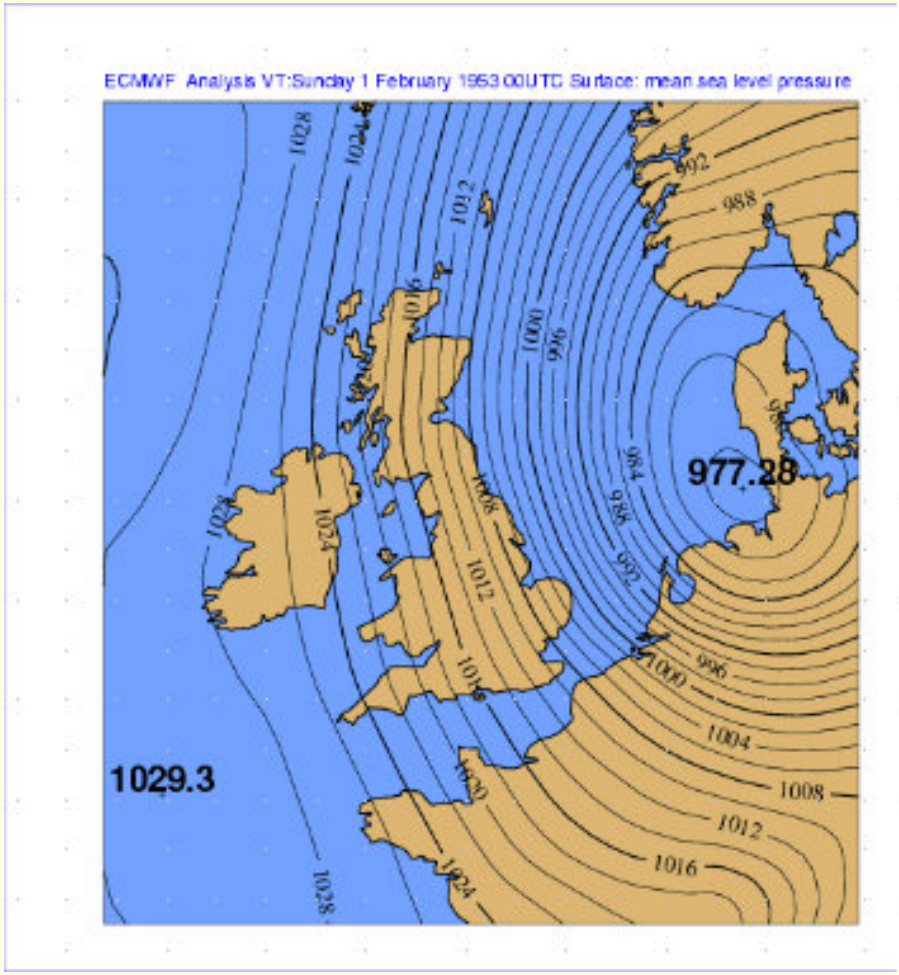
- **Occurred on 31 Jan/1 Feb, 1953.**
- **Greatest storm surge on record for the North Sea**
- **100,000 hectares flooded and more than 300 people lost their lives In eastern England.**
- **5 dykes burst and 1,800 people drowned in Holland.**
- **The *Princess Victoria* sank in the North Channel.**

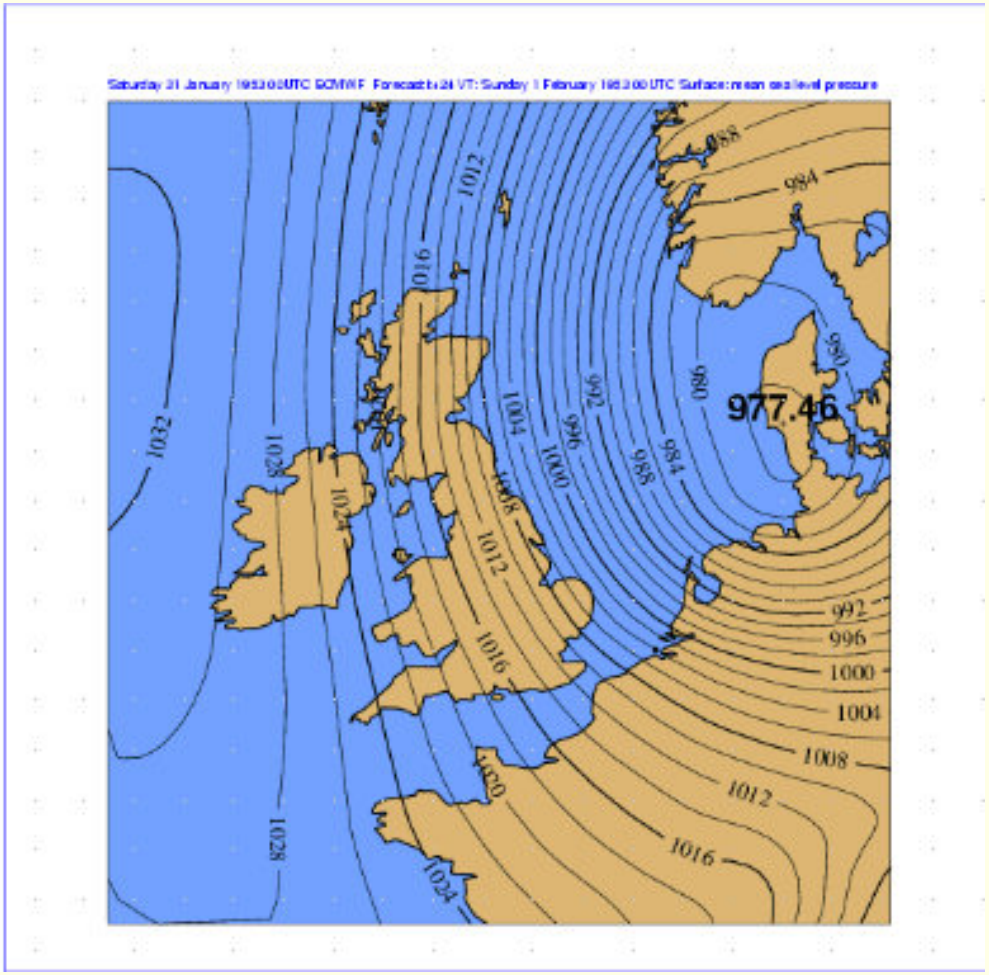




PMSL **V10m**

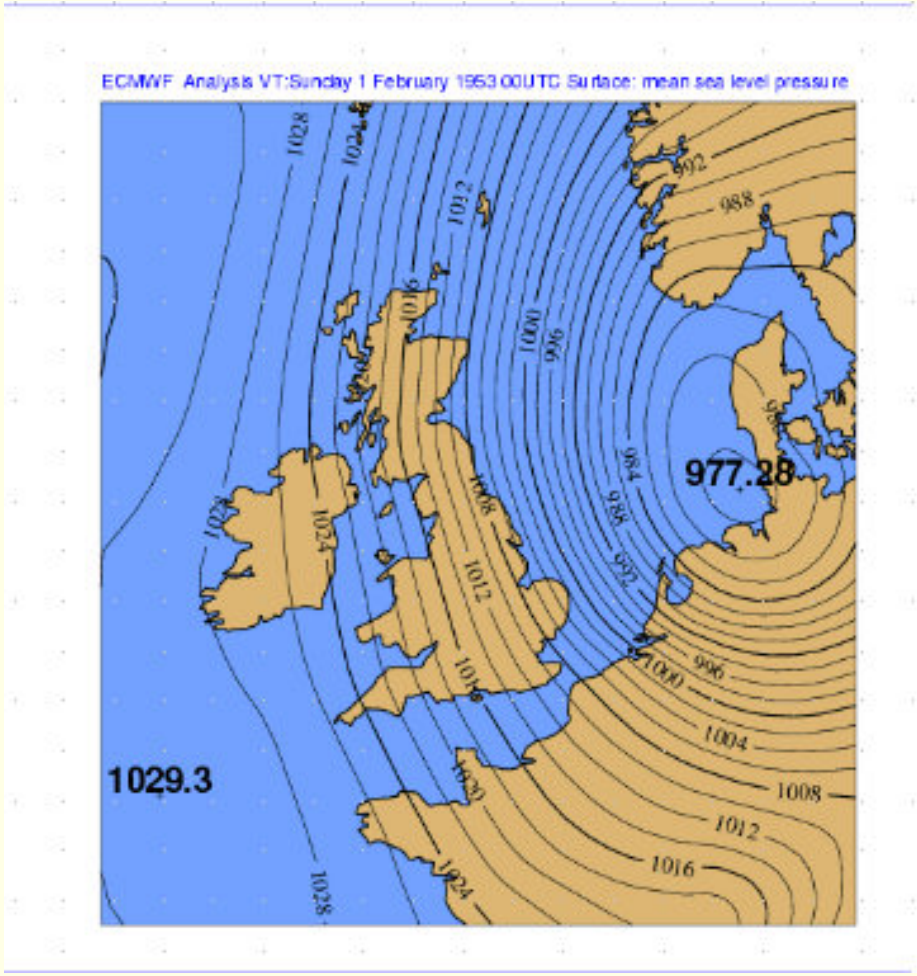
Analysis, 00 UTC, 1 February, 1953



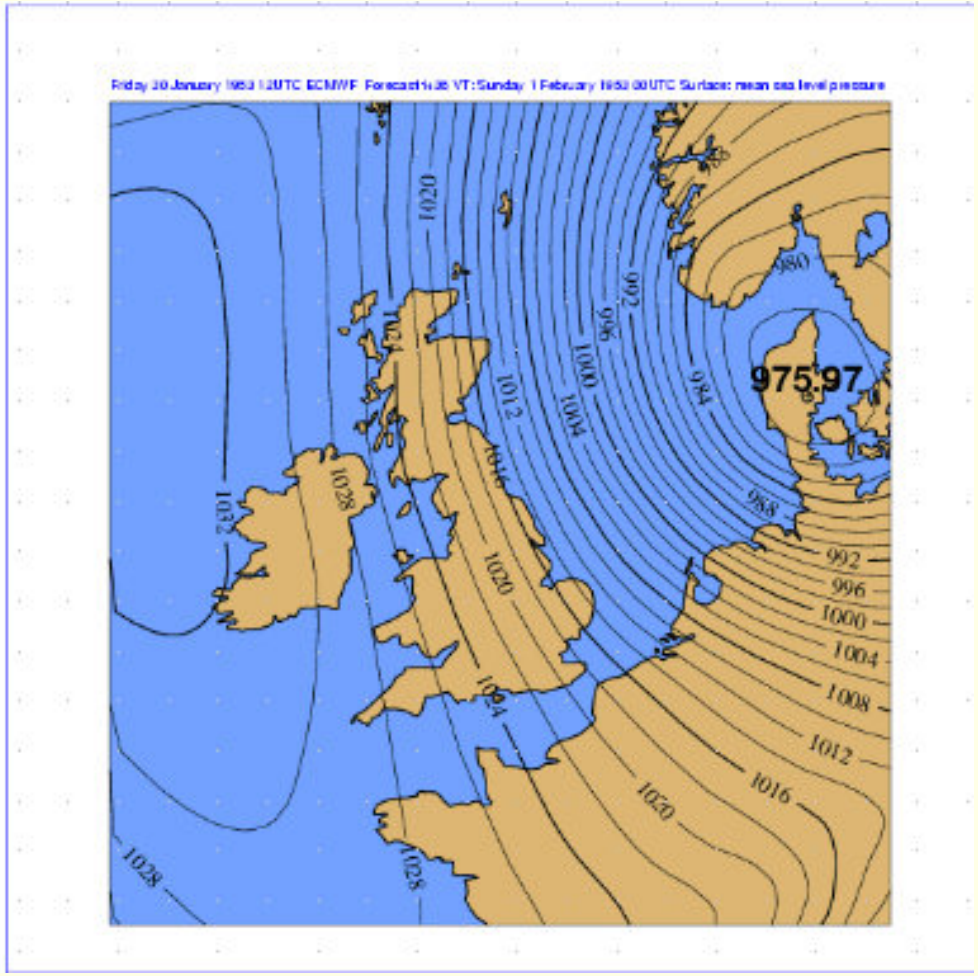


Analysis

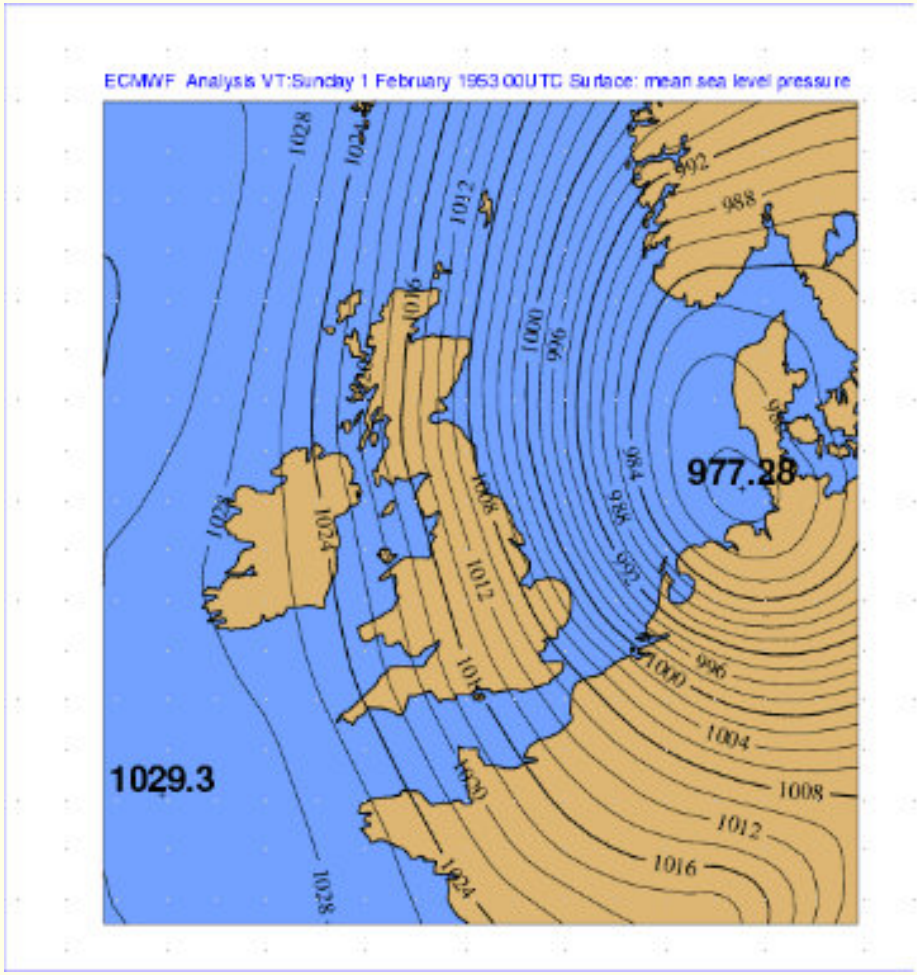
24-h Forecast

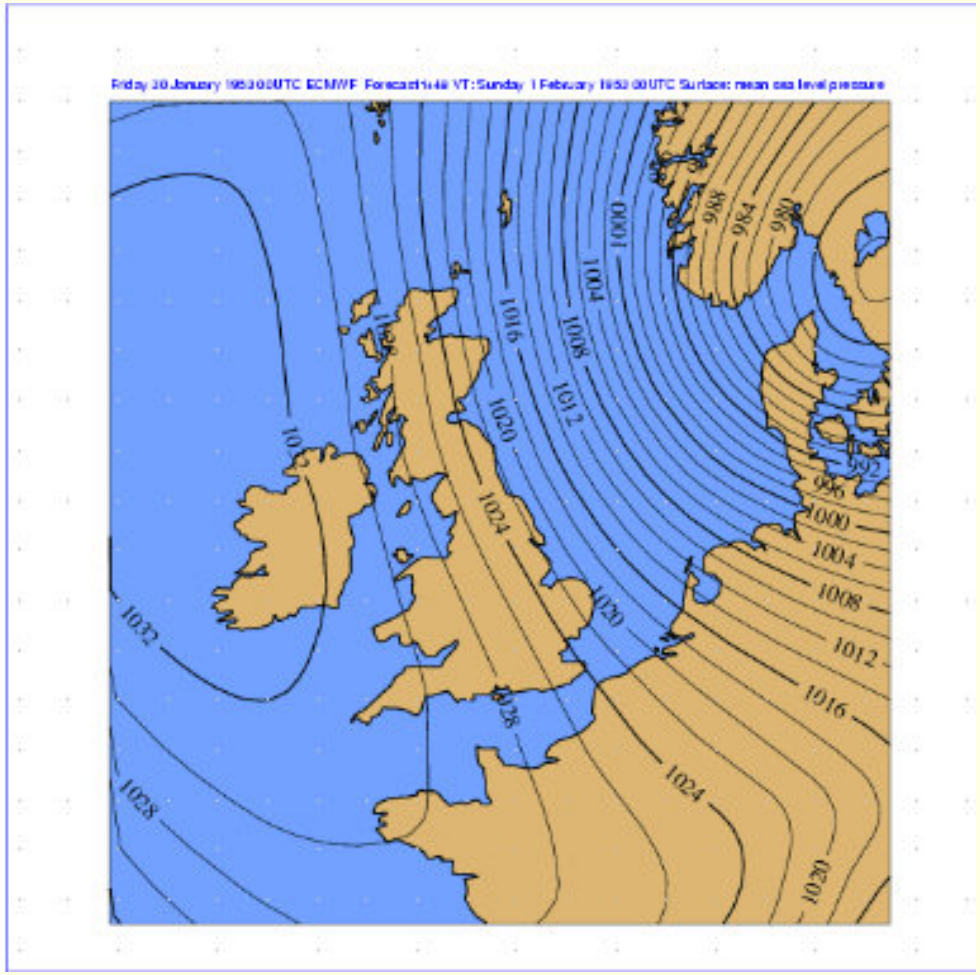


Analysis

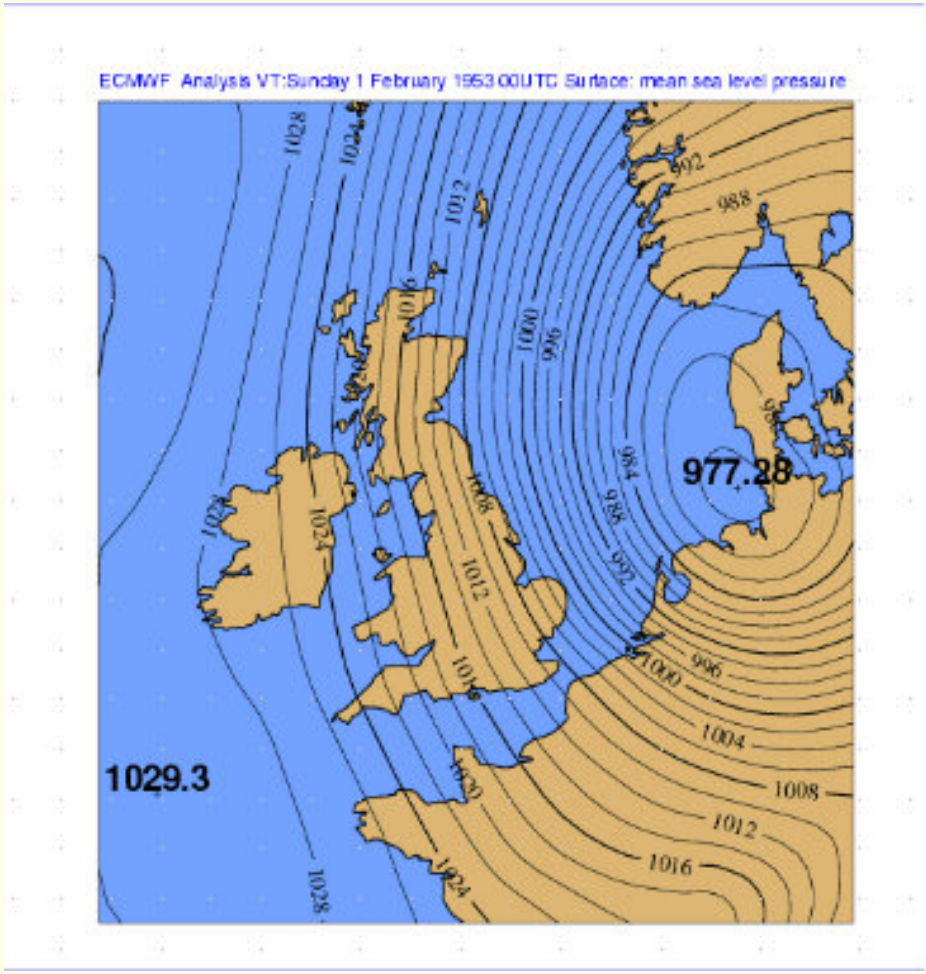


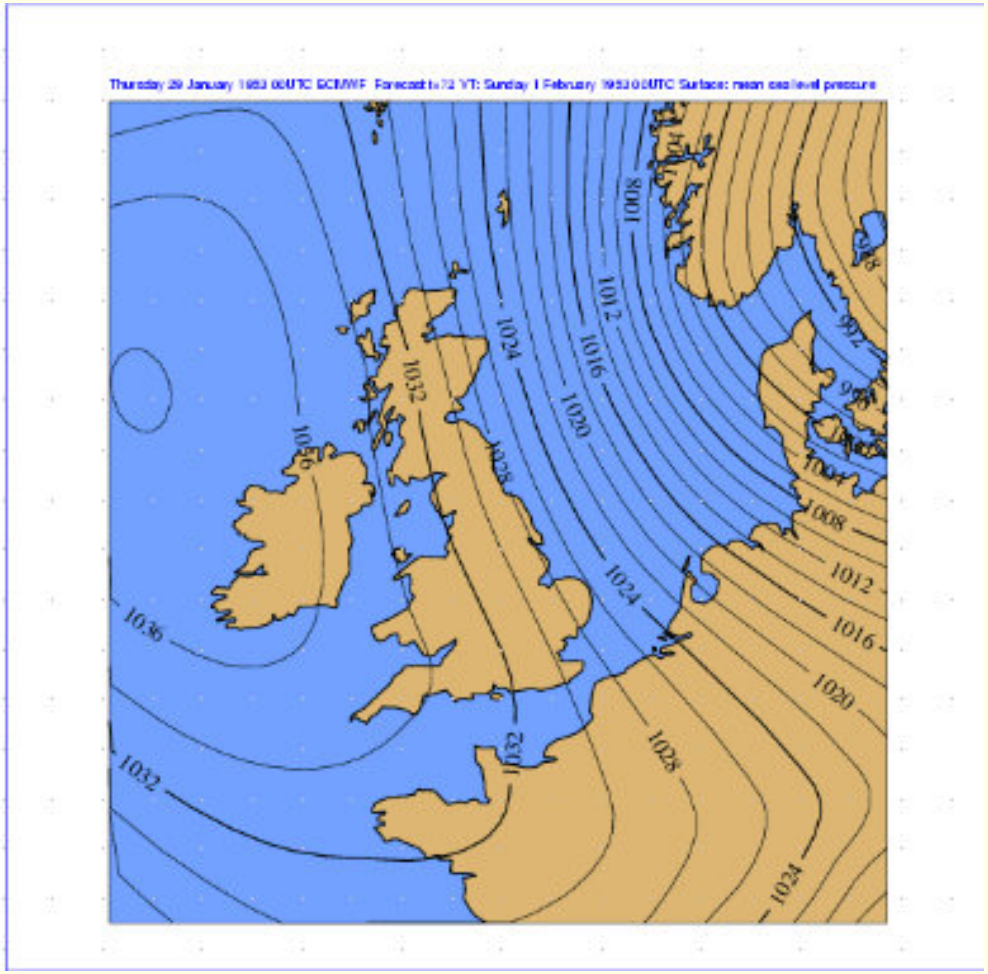
36-h Forecast





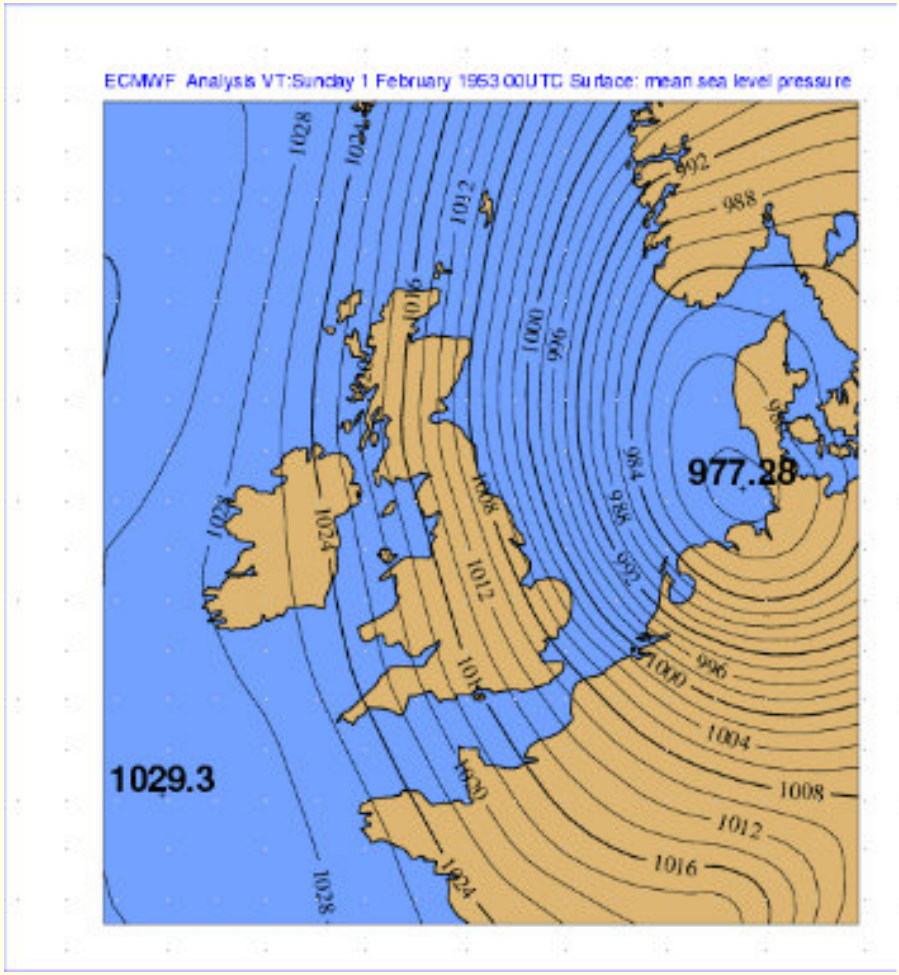
Analysis **48-h Forecast**

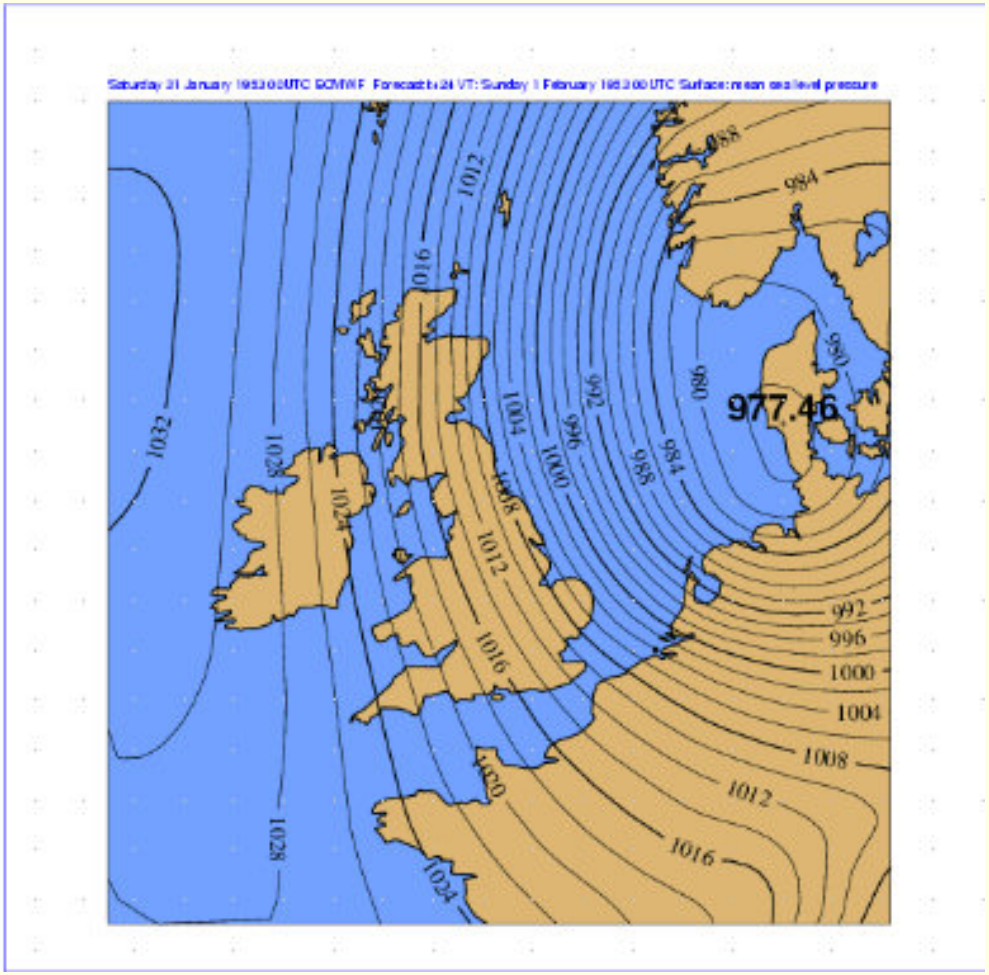




Analysis

72-h Forecast

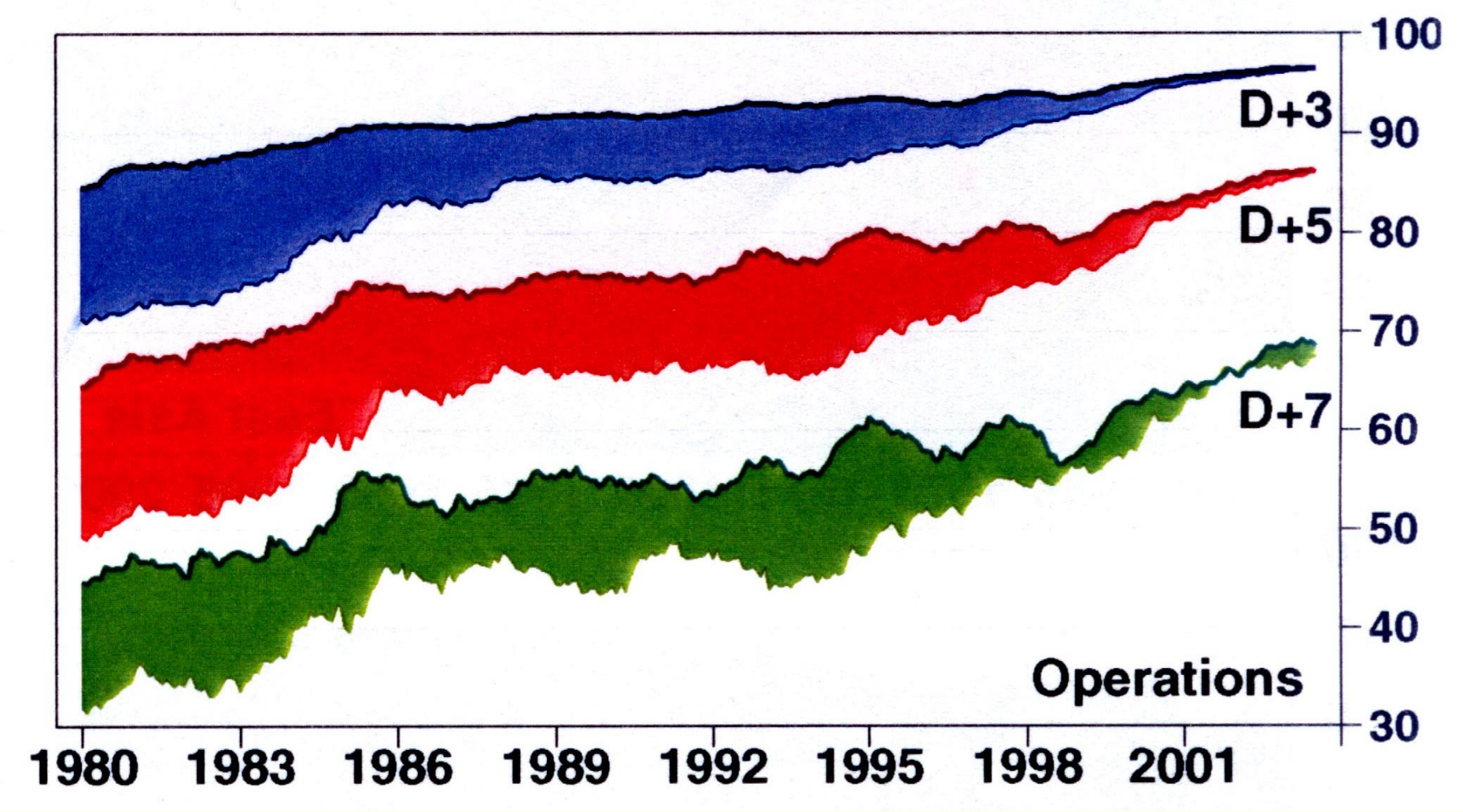




Analysis

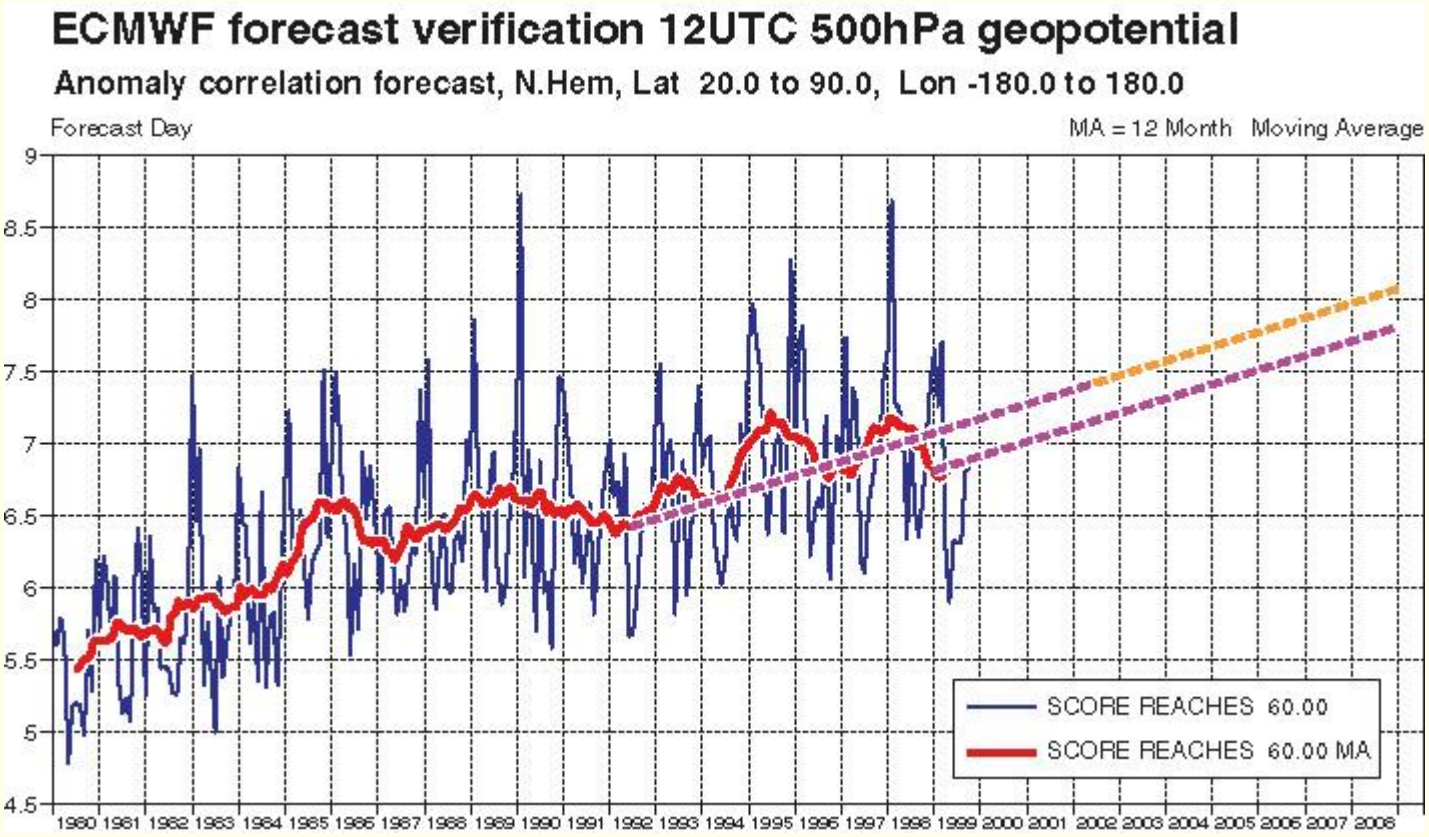
24-h Forecast

Anomaly Correlations: Operational



Anomaly Correlation of 3, 5 and 7 day 500 hPa forecasts for extra-tropical northern and southern hemispheres.

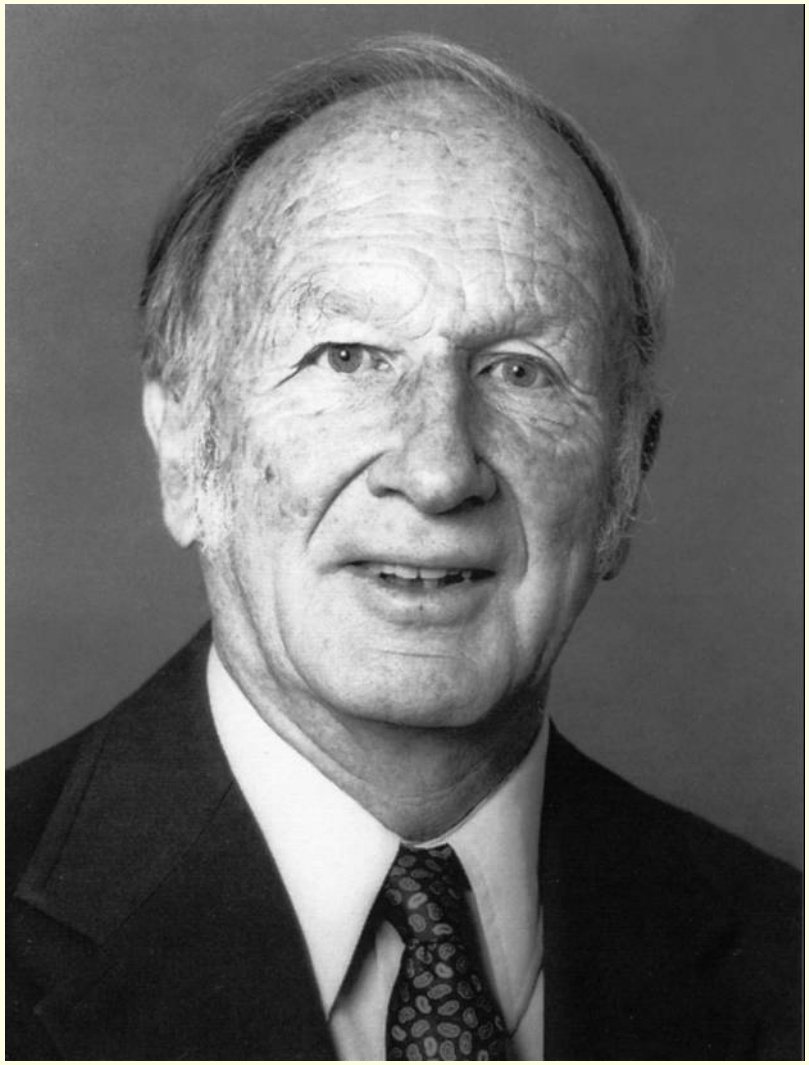
Progress in numerical weather prediction over the past fifty years has been quite dramatic.



Forecast skill continues to increase . . .
by one day per decade.

However, there is a limit . . .

Chaos in Atmospheric Flow



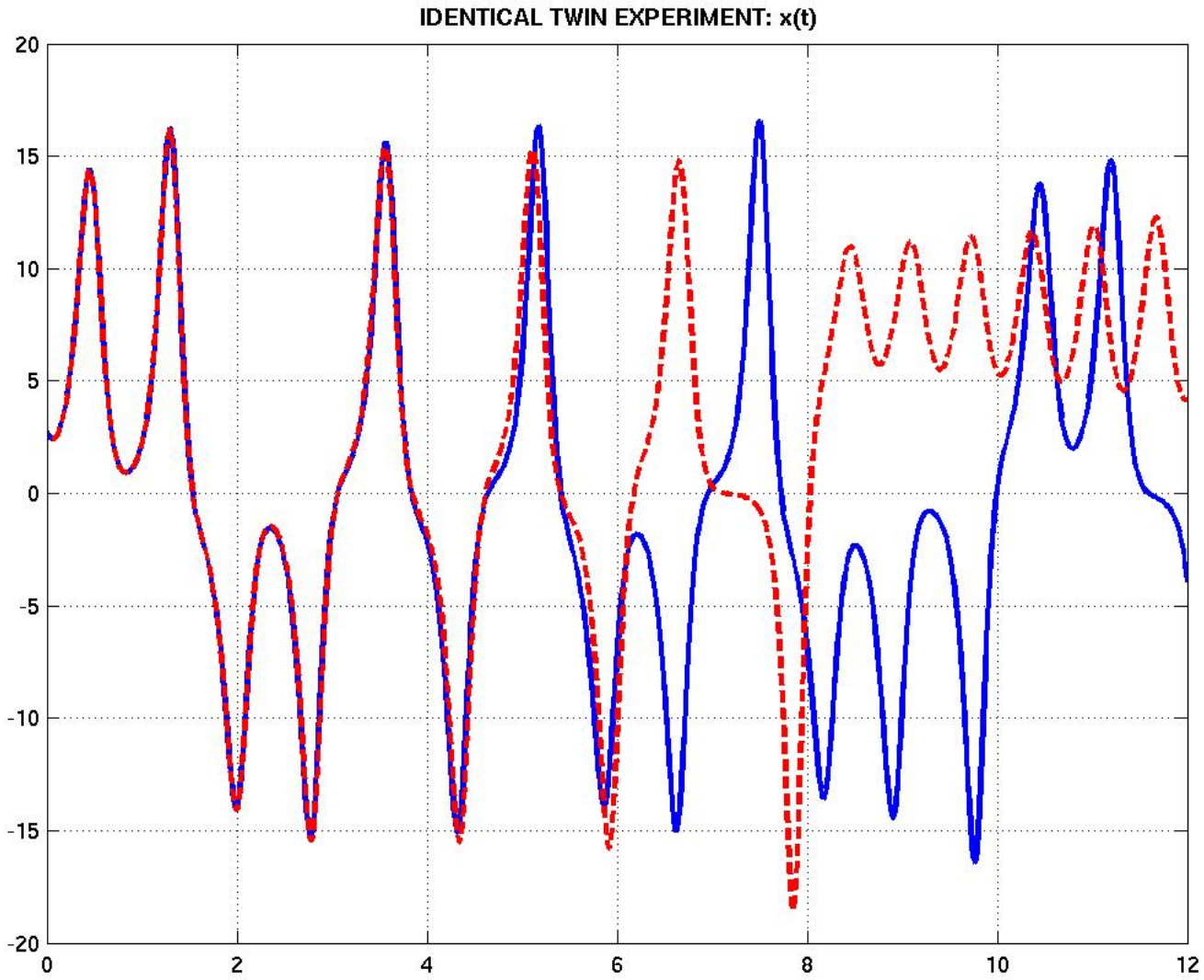
Edward Lorenz (b. 1917)

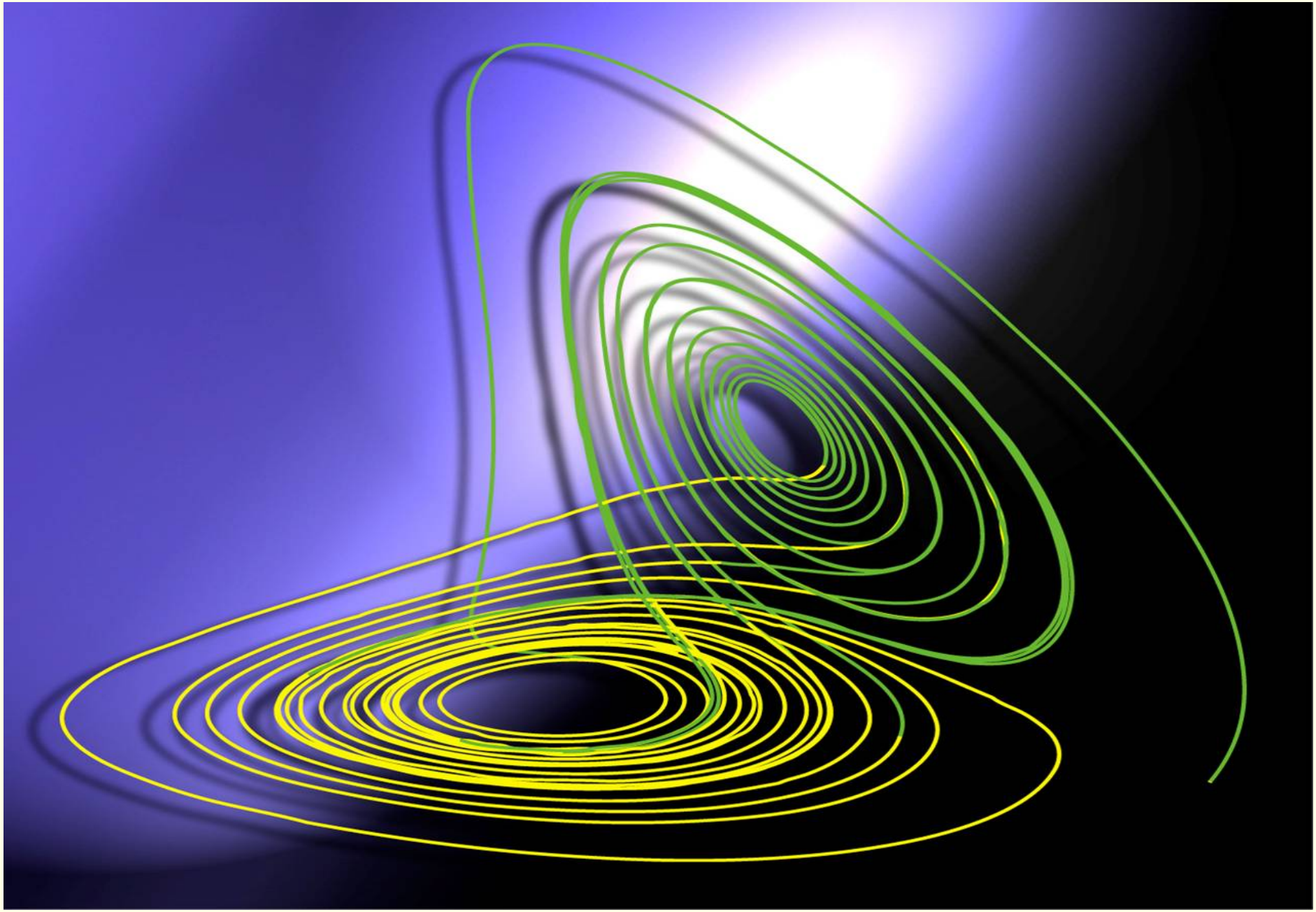
In a paper published in 1963, entitled *Deterministic Nonperiodic Flow*, Edward Lorenz showed that the simple system

$$\dot{x} = -\sigma x + \sigma y$$
$$\dot{y} = -xz + rx$$
$$\dot{z} = +xy - bz$$

has solutions which are highly *sensitive to the initial conditions.*

Identical Twin Experiment





The characteristic *butterfly pattern* in Lorenz's Equations.

Lorenz's work demonstrated the practical impossibility of making accurate, detailed long-range weather forecasts.

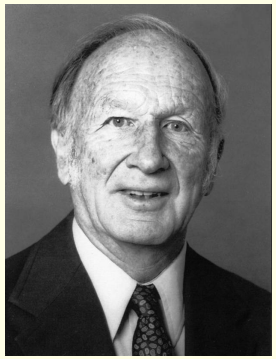
In his 1963 paper he wrote:

"... one flap of a sea-gull's wings may forever change the future course of the weather."

Within a few years, he had changed species:

"Predictability:
does the flap of a butterfly's wings in
Brazil set off a tornado in Texas?"

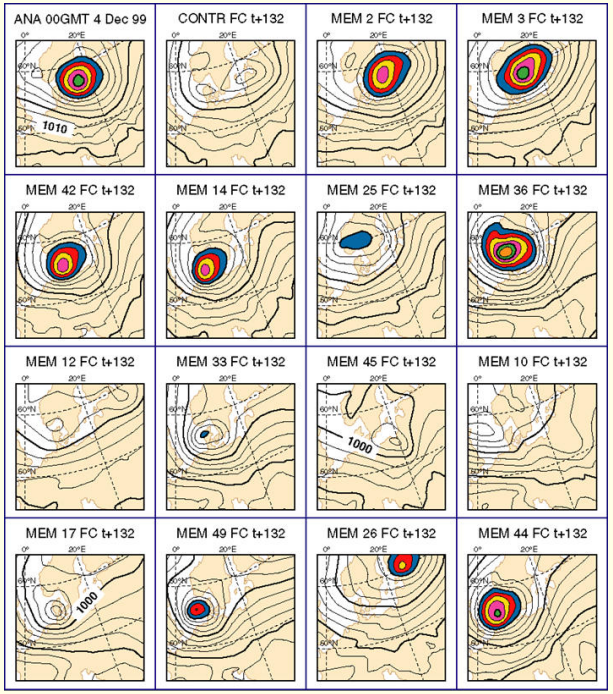
[Title of a lecture at an AAAS conference in Washington.]



Lorenz demonstrated, with skill,
The chaos of heat-wave and chill:
Tornadoes in Texas
Are formed by the flexes
Of butterflies' wings in Brazil.

Overcoming Chaos

Ensemble prediction is our means of overcoming the obstacle of chaos in the atmosphere.



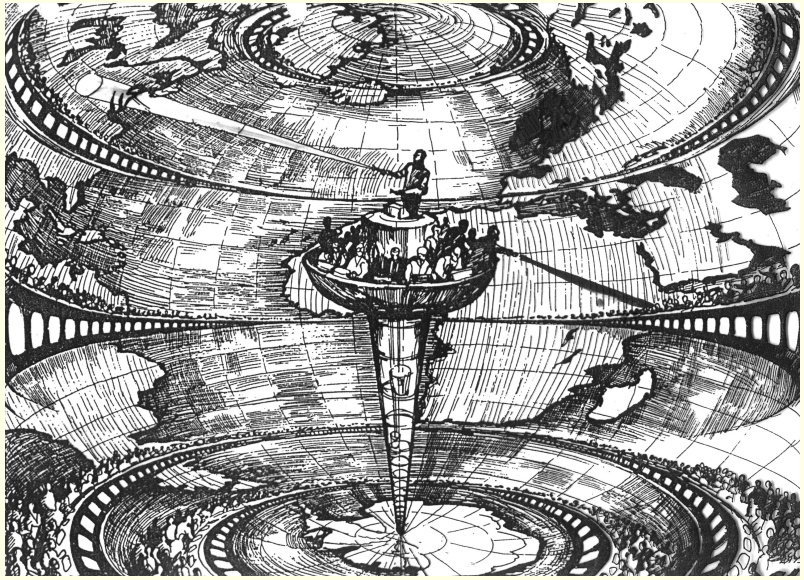
Analysis (top left), and 15 132-hour forecasts of sea-level pressure starting from slightly different conditions.

Deterministic forecasts
are replaced by
probability forecasts.

Richardson's Dream

"Perhaps some day in the dim future it will be possible to advance the computations faster than the weather advances . . . . But that is a dream."

Forecast Factory *versus* MPP

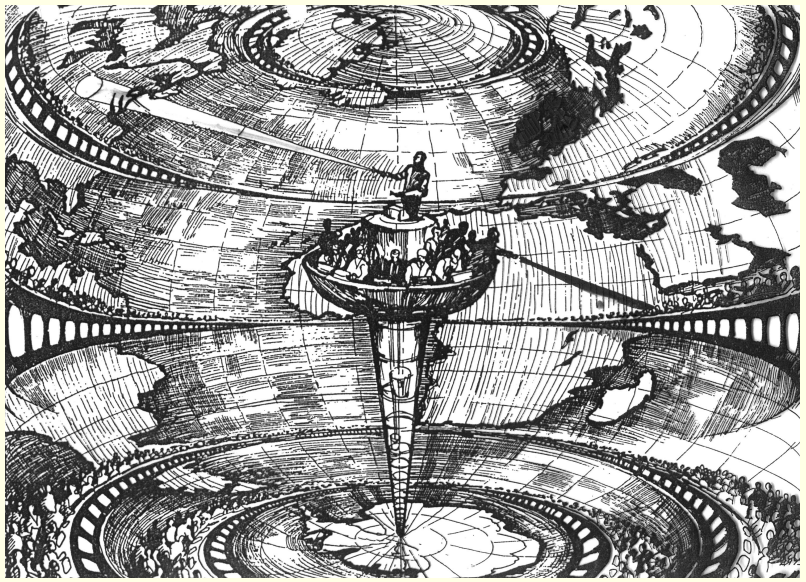


Richardson's *Forecast Factory* had 64,000 'computers'.

The fastest computer (TOP500, June 2005) is the IBM BlueGene/L with 65,536 processors!

64 K

Forecast Factory *versus* MPP



The IBM machine is rated at 136.8 TFlops nine orders of magnitude faster than Richardson's Factory.

The logical structures are similar: message-passing, domain decomposition, task synchronization and control.

Richardson's *Forecast Factory* had 64,000 'computers'.

The fastest computer (TOP500, June 2005) is the IBM BlueGene/L with 65,536 processors!

64 K

Concluding Remarks

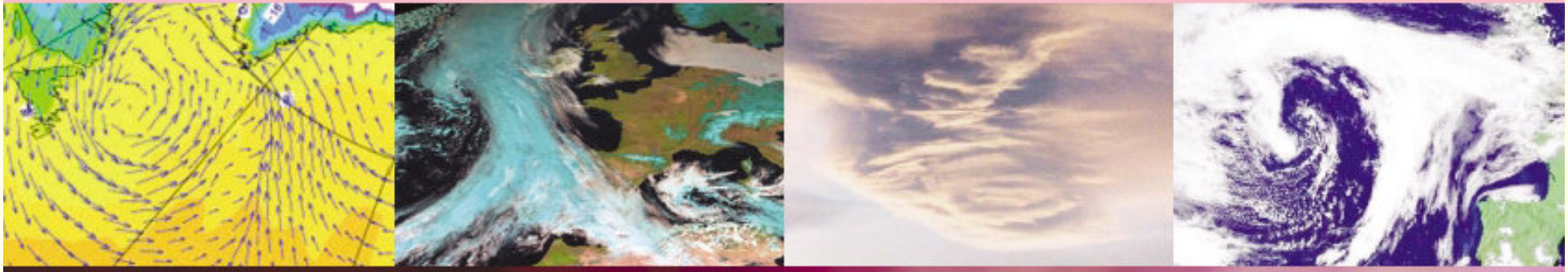
- ***Weather Prediction is now based on solid scientific foundations***
- ***Forecast skill is increasing by one day per decade***
- ***Predictability horizon is overcome by means of probability forecasts***
- ***Climate models give useful guidance on a decadal time range***
- ***There remains much to do, especially on smaller space and time scales.***

The End

Typesetting Software: TEX, *Textures*, LATEX, `hyperref`, `texpower`, Adobe Acrobat 4.05
Graphics Software: Adobe Illustrator 9.0.2
LATEX Slide Macro Packages: Wendy McKay, Ross Moore

M.Sc. Meteorology

A new M.Sc. in Meteorology in partnership with Met Éireann covering Theory and Applications.

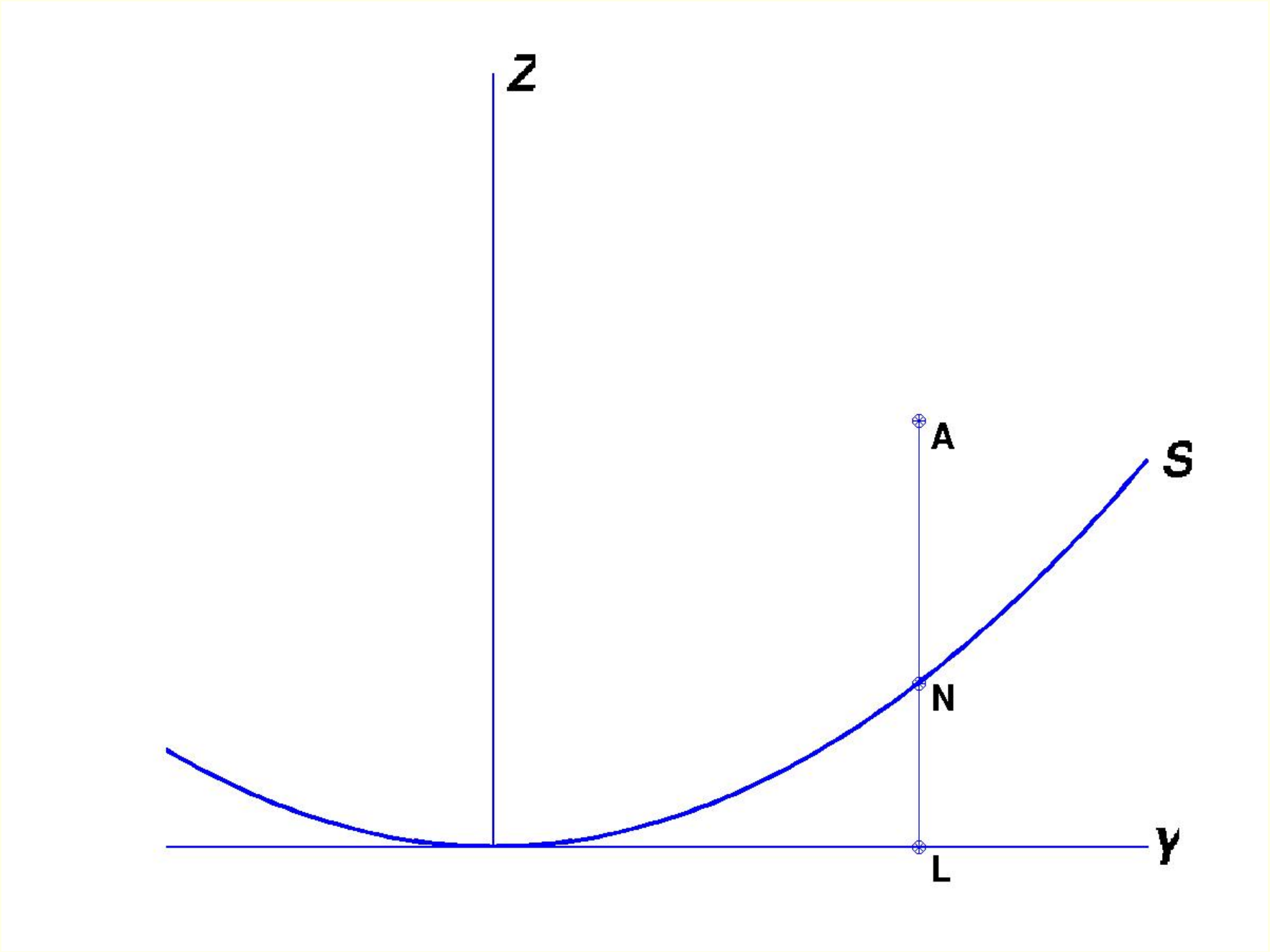


Modules:

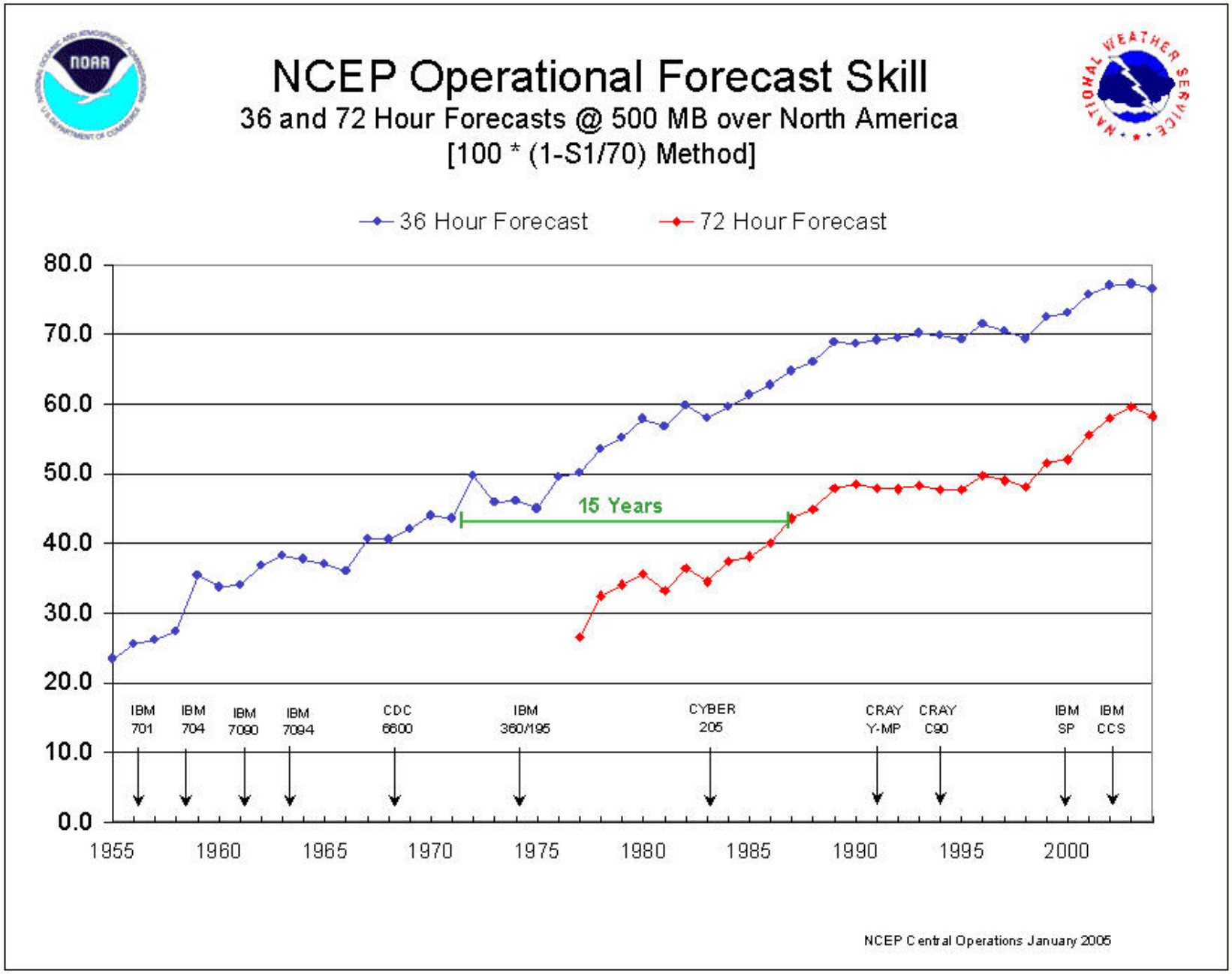
- General and Physical Meteorology
- Climate and Synoptic Meteorology
- Dynamic Meteorology
- Numerical Weather Prediction

Hands on experience in an extended applied project, field trip and practical applications. For graduates in science and engineering with a strong mathematical background

www.ucd.ie/meteorology



The slow manifold



NMC/NCEP Scores: The longest verification series in existence.